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Swedish University of Agricultural Sciences

Department of Soil and Environment

Minimized nutrient leaching through fertilizer management

– An evaluation of fertilization strategies

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Abstract

Nutrient leaching causing surface- and groundwater pollution and eutrophication is one of the main environmental problems of modern society. Plant production is among the quantitatively most important sources of nutrient leaching, particularly of nitrogen and phosphorus, which stands in focus in remediating these problems. One of the most important measures to be taken is to apply fertilizers in a correct way to meet the needs of the plants while preventing any nutrients to leach. The rather unnoticed theory and method of the demand-driven fertilization strategy, which means to supply the plant with nutrients according to its momentary demand, was compared with representative fertilization strategies commonly used in current commercial plant production. Then the demand-driven driven strategy was compared with three other strategies in a pot experiment: (1) a linear nutrient supply on a daily basis, (2) an approximately linear nutrient supply added twice a week, and (3) a onetime application with all the fertilizers added in the beginning. Uptake and leaching of N and P was measured for all treatments. The results clearly showed that the demand-driven strategy leached the least and had the highest uptake in relation to the added amount of N and P, and that the onetime application leached the most. It was concluded that the demand-driven strategy had highest potential in amending nutrient leaching, and that further studies most likely would be fruitful.

Popular scientific abstract in Swedish

Behovsanpassad gödsling som ger höga skördar utan att belasta miljön

Behovsanpassad gödsling

I ett kärlförsök jämförde jag en unik och förvånansvärt ouppmärksammad gödslingsmetod kallad behovsanpassad gödsling, som utvecklades vid SLU för ett antal decennier sedan, med traditionell gödsling.

Hur olika gödslingsmetoder inverkar på miljön

Jag jämförde fyra olika metoder att förse växter med växtnäring och mätte både växternas näringsupptag och näringsläckage vid flera tillfällen under tillväxtperioden. De fyra metoderna var: (1) all växtnäring tillsattes i en giva handelsgödsel när odlingen påbörjades, (2) växtnäring tillsattes med bevattningsvattnet i lika stora småportioner 2 gånger per vecka igenom hela försöket, (3) växtnäring tillsattes med bevattningsvattnet i lika stora småportioner dagligen igenom hela försöket, och (4) växtnäring tillsattes på samma sätt som i (3) med skillnaden att mängden växtnäring varierade med växtens behov, s.k. behovsanpassad gödsling. Solrosplantor i krukor odlades och mängden växtnäring i växterna och i lakvattnet som samlades upp under krukorna analyserades kontinuerligt.

Resultaten var entydiga; behovsanpassad gödsling ledde till högst upptag av tillsatt växtnäring och minimerade näringsläckage. Alla former av näringstillförsel via bevattning kan förebygga näringsläckage jämfört med gödsling i fast form. Det som visade sig vara mest optimalt var att fördela gödselgivan under hela växtsäsongen efter växtens behov tillsammans med bevattningen, och minst optimalt var att ge en stor giva handelsgödsel vid ett enda tillfälle vid påbörjat odlingstillfälle.

En mycket positiv aspekt är att behovsanpassad gödsling med bevattning dessutom ger lika höga, eller högre skördar, än de andra metoderna. För en professionell odlare måste det finnas en möjlighet att installera en bevattningsanläggning och att det är lönsamt för odlaren att investera i ett sådant system. För hobbyodlaren är det enklare. Han kan tillföra växtnäringen efter behov när han vattnar.

Olika miljöproblem till följd av att gödsling inte är optimal

Övergödning av våra vatten, såväl sjöar som hav, är ett stort problem på många platser. Detta påverkar främst floran och faunan i våra vatten på ett negativt sätt, men även samhällets dricksvattenkvalitet, giftiga algblomningar på badplatser och kan även utgöra en en större belastning av både reningsverk och vattenverk .

Övergödning och försämrad vattenkvalitet beror till stor del på näringsläckage, dvs växtnäring som inte kommer växterna till godo, utan som istället via grundvattnet hamnar i vattendrag och slutligen i sjöar och hav. För att förhindra dessa problem är det viktigt att på alla sätt optimera växttnäringstillförseln och på så sätt minimera näringsläckaget. Det innebär att använda den gödslingsmetod som möjliggör att växterna tillgodogör sig den tillförda näringen i så hög grad som möjligt är en mycket anglägen uppgift.

Behovsanpassad gödsling har stora förutsättningar att bidra med just detta. Om man i ett odlingssammanhang använder bevattning, kan behovsanpassad gödsling minska näringsläckaget påtagligt. Eftersom metoden dessutom påvisat goda skörderesultat finns det ett ekonomiskt motiv för producenter att tillämpa den. En ytterligare positiv effekt med metoden är att den kräver mindre mängd gödsel per producerad mängd skörd, vilket är en ekonomisk fördel för odlare och för hushållningen med ändliga resurser.

Slutligen, när metoden togs fram, upptäcktes det att landlevande växter har ganska likartat behov vad gäller sammansättningen av gödselmedel. Detta gör att metoden är relevant för de flesta odlare, och kan tillämpas på olika befintliga gödslingsmetoder.

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Introduction

A controversial theory of plant nutrition caught my interest

As a student at the Swedish University of Agricultural Sciences (SLU), becoming an agronomist, I encountered very different opinions and perceptions concerning the nutritional requirements of terrestrial plants. There are many aspects of plant nutrition. The area that first caught my attention was the ratios of mineral nutrients in fertilizers supplied vs. those in the plants. My interest awoke when I encountered a controversial theory of plant nutrition that created disagreement among the student colleges, especially those with farming background. This interest led me to my bachelor thesis: “Do plants require nutrients in similar proportions?” (Nachmansohn 2014), in which I wrote extensively on the topic of required nutrient ratios. However nutrient ratios are only one part of the theory. Another major part of the theory concerns nutrient supply and its potential to increase nutrient use efficiency and decrease leaching. The theory has received very little attention, especially in light of its claims. Still, it is founded on decades of genuine research. Torsten Ingestad, the leader of the research team at SLU, received the Wallenberg Prize in 1989, also known as the small Nobel Prize, for his efforts and innovation in the field of plant nutrition. My interest and curiosity in nutrient supply and leaching has all but diminished. Therefore, my master’s thesis had the aim to investigate the potential of Ingestads theory on plant nutrition with regard to nutrient leaching and compare it with other theories.

Nutrient leaching

Nutrient leaching from terrestrial ecosystems is one of the main environmental problems of modern society. The leaching causes surface- and groundwater pollution and eutrophication. Agriculture and plant production are among the quantitatively most important sources of nutrient leaching (Blombäck *et al.* 2011, Ejhed *et al.* 2011). Arable land can be the source of approximately fifty per cent of a nation’s annual anthropogenic load of both nitrogen and phosphorus, which finally ends up in the sea (Blombäck *et al.* 2011, Ejhed *et al.* 2011).

Fertilizer management is one of the main factors that influence the quantity and rate of nutrient losses from arable land and plant production through leaching (Blombäck *et al.* 2011, Ejhed *et al.* 2011). Therefore, handling of fertilizers is a key factor in reducing nutrient leaching from arable land and plant production. Thus, it is of pivotal importance to adjust fertilization strategies in order to minimize nutrient leaching and its derivatives.

Fertilization strategies

As regards fertilization, the aim is to provide nutrients to plants at the right time, in correct doses, and prevent leaching of nutrients from applied fertilizer. Fertilizer applied in a way that it is not entirely utilized by the plants will end up in at least one of the following posts: (1) drainage losses, (2) adsorbed by the soil, or (3) processed by microbes. Nutrients that leave the production system through emissions into the air are included in the microbial processes. All open, soil based systems leach nutrients, even though leaching is greater from some types of ecosystems compared to others. In agriculture and open-land horticulture, nutrient losses through leaching are often found to be high (Blombäck *et al.* 2011, Ejhed *et al.* 2011). This is also true for several forms of greenhouse production systems and turf-management (Barton and Colmer 2005, Stirzaker 1999). In many places of the world, particularly in Europe and non-arid North America, nutrient losses through leaching over all, are found to be very high. This problem has been addressed by researchers, environmental agencies and policy makers (Beaudoin 2005, Blombäck *et al.* 2011, Ejhed *et al.* 2011, Power 1989).

Several fertilization strategies can be applied, with the aim to minimize nutrient losses through leaching while at the same time maintaining the desired yield quantity and crop quality. The strategies are primarily defined by two things: (1) the limitations in the type of production system in which they are used, and (2) by the preconceptions, held by producers and researchers, of how the soil-plant/soilless-plant system works. Practiced fertilization strategies are listed below:

1. Fertilization based on solid inorganic fertilizers
2. Fertilization based on solid organic fertilizers
3. Fertilization based on nutrient solutions
    a. based on amounts per unit of time
    b. based on concentrations in the solution
    c. based on amounts on demand

In this study these strategies and methods were compared regarding effect on leaching using literature data and a greenhouse experiment.

Inorganic fertilizer based strategies

In these strategies, inorganic fertilizers, consisting of easily soluble mineral salts, are applied considering three main factors; timing, total amount, and number of distribution occasions. Timing refers to when it is optimal to apply fertilizers in relation to sowing, growth and physiological state in crop (Barłóg and Grzebisz 2004). Total nutrient amount and the number of occasions to distribute refer to yield and risk for leaching, but also nutrient use efficiency and crop qualities, such as size and protein content of the ears (Johansson *et al.* 2004). This strategy is very common in agriculture and open land horticulture.

The most important fertilizer factor that influences leaching in a long-term perspective is total N input (Davies and Sylvester-Bradley 1995), of which in general most ends up in the plant and a smaller portion is lost through leaching. Most N that leaches is in the form of nitrate (Neeteson *et al.* 2003), and from leaching in field vegetable production. Decomposition of crop residues remaining on the field and mineral N present in the soil at harvest, i.e. residual soil mineral N, are the main sources of nitrate leaching. Whether N in crop residues or residual soil mineral N is the major source, depends on the type of crops grown (Neeteson *et al.* 2003). However, the total amount N added to the system is not the only factor that matters. It depends on production system and crop, and correct timing of the fertilizer application in relation to the crops plant development can decrease leaching (Davies and Sylvester-Bradley 1995). Certainly, adapting the total amount of fertilizer to prevalent growth conditions by distributing it on more than one occasion is preferable to improve nutrient use efficiency and decrease leaching (Engström and Bertilsson 2014), especially if the system is subject to heavy rains. Modern technology in the form of N-sensors, especially if calibrated against reference crops, have increased the ability to provide the crop with N more on demand, which in turn has a positive effect on the leaching problem (Engström and Bertilsson 2014).

It must also be noted that, in field production that employ solid easily soluble fertilizer, the N leaching can be due to some mismanagement, like adding more fertilizer than recommended. This obviously leads to more nutrient leaching (Davies and Sylvester-Bradley 1995, Neeteson *et al.* 2003).

Agriculture and open land production are complex systems, and we mainly understand them empirically. Many factors control the leaching processes and it is countermeasures, of which catch crop might be most important in reducing leaching, rather than the fertilization strategy (Constantin *et al.* 2009, Kirchmann and Bergström 2007). Most leaching takes place after the growing season, and even if crop uptake of added N is 100 %, much of it could leach from the crop residues (Neeteson *et al.* 2003). If fertilizer is applied to achieve maximal yield, the system will leach even with other measures taken against leaching.

Organic fertilizer based strategies

In these strategies different kind of animal or green manure, are applied to or incorporated into the soil, according to the same basic principles as in the inorganic fertilizer based strategy. But there are some major differences. Manure that must be incorporated into the soil can only be applied before sowing. Furthermore, due to the lack of control of the net mineralization rate of the manure, timing, total amount and the number of occasions to distribute it are the factors that determine yield, leaching and practical possibilities to apply the manure (Pang and Letey 2000, van Es *et al.* 2006). This strategy is common in agriculture and open land horticulture.

The production systems that employ this strategy are the same kind that employs the inorganic fertilizers, i.e. classical farms that uses solid fertilizers. One difference is that most organic fertilizers have no alternative option for timing or distribution, than to apply the whole N-give prior to sowing. Even the total amount of added nutrients is sometimes only a rough estimate, and even when estimates are accurate, it is hard to predict how much of the nutrients applied will become available to the plant when needed. All these uncertainties increase the risk of (1) applying to much N, and (2) decreased plant availability, which in turn increase the risk for leaching.

Bergström and Kirchmann (1999; 2004; 2006) have made several studies comparing organic and inorganic fertilizers and how they affect nutrient leaching. Nutrients taken into consideration were nitrogen and phosphorus. The research group has compared leaching and crop uptake of nitrogen after application of green manures and ammonium nitrate fertilizer, poultry manure and ammonium nitrate fertilizer, and leaching and crop uptake of nitrogen and phosphorus from pig slurry at different application rates.

Their research has shown that nitrogen use efficiency in plants is significantly higher when grown with mineral fertilizers compared to when grown with green manure (Bergström and Kirchmann 2004). Their results have further suggested that the potential for nitrogen leaching in the long-term is significantly larger from animal manures than from inorganic nitrogen fertilizers (Bergström and Kirchmann 1999, 2006). Their research has also shown that the use efficiency of added phosphorus was best when the source was inorganic fertilizer (Bergström and Kirchmann 2006). Their conclusion is that “from both a production and water quality viewpoint” inorganic fertilizers are superior to organic manure in general (Bergström and Kirchmann 2006).

If the N-dose is sufficient to ensure maximal yield, it is probable that high leaching losses occur after the growing season if animal manure is used (Kirchmann and Bergström 2007, Pang and Letey 2000). The same applies for green-manure.

Fertigation based strategies

Fertigation is the method of supplying plant nutrients together with irrigation water. In this strategy different kinds of fertilizers are used according to a variety of application schemes. The application schemes are defined by the framework and limitations of the plant production system, and this in turn is depending on which theory on how to best supply crops with nutrients that is adopted (Barak 2007, Bar-Yosef 1999, Jat *et al.* 2011, Singh 2012). Through this strategy one can virtually supply almost any amount of nutrients at any time during growth. Main factors considered in fertigation systems are the correlation to water and nutrient use efficiency and nutrient losses (Barak 2007, Bar-Yosef 1999, Jat *et al.* 2011, Singh 2012). In fertigation, fertilizers can only be supplied as solutes. For this reason, fertigation generally employs completely water soluble inorganic fertilizers, even though it can employ organic fertilizers if they are in a liquid form. This virtually limits the use of organic fertilizers to urine only.

Fertigation is common in production system based on irrigation, such as greenhouse production, and agriculture and open land horticulture in arid areas.

Fertigation has the potential to ensure that the right amounts of water and nutrients are available in the root zone, satisfying the plants total and temporal requirement of these two inputs (Singh 2012). Fertigation has, since it was established in Israel 1969, been shown to have several advantages and has spread rapidly and has become a commonly used method all over the world (Jat *et al.* 2011). Fertigation brings about a higher nutrient use efficiency compared to conventional application of fertilizers (Barak 2007). Furthermore, fertigation entails a more sustainable soil management with less polluted ground and surface water pollution through nutrient leaching (Jat *et al.* 2011, Singh 2012). Consequently, fertigation entails better resource conservation, as it "helps in saving of water, nutrients, energy, labor and time" (Jat *et al.* 2011).

Fertigation according to amount of fertilizers per unit of time

In open-land agriculture and horticulture, fertilizer is commonly added to irrigation water at different amounts per unit of time by dosing equipment according to a computer program.

Reduced leaching under fertigation, without a decline in yield or quality, or even with higher yields, has been reported for annual crops, e.g., for tomato (Miller *et al.,* 1976), for celery (Feigin *et al.,* 1982), for fruit trees (Dasberg *et al.,* 1988; Boman, 1996) and common agricultural crops (e.g. wheat, Kätterer and Andrén 1996).

Even though fertigation can be applied in virtually any irrigation system, such as flood, furrow, and sprinkler irrigation, micro-fertigation, i.e. fertilizer application through a drip-irrigation system is the most efficient way to utilize fertigation (Bar-Yosef 1999, Jat *et al.* 2011). Nutrient losses through leaching are very small from micro-fertigated systems.

However, there are examples of problems with leaching in fertigation based systems, and "fertigation may favor leaching of NO_3-N" (Singh 2012). Fertigation easily leads to nutrient leaching if the soils' permeability and irrigation schemes are not matched correctly (Barak 2007, Bar-Yosef 1999, Jat *et al.* 2011, Singh 2012). Thus, there can be problems with significant nutrient leaching even from fertigation systems (Barak 2007, Bar-Yosef 1999, Jat *et al.* 2011, Singh 2012).

Concentration-driven strategy

Another way to employ fertigation is to work with concentrations instead of amounts of fertilizers in the irrigation water. The nutrients are supplied to the plant by applying a nutrient solution to the rhizosphere, which has a certain concentration of each nutrient and a certain total ion concentration of the solution as a whole. These concentrations are correlated to uptake rate, growth and development in plants. The purpose is to maximize yield per area and quality of the product. This strategy is virtually limited to the use of completely water soluble inorganic fertilizers only, as there is no other way to control the ion concentrations in the nutrient solution with sufficient precision. This strategy is mainly used in greenhouse production of soilless culture with a closed or semi-closed recirculation system for reuse of the nutrient solution (Sonneveld 2002, Sonneveld and Welles 1988). However, it is also used to some extent in greenhouse production in soil based culture (Barak 2007, Breś 2009, 2010).

Nutrient leaching from production systems that employ a concentration-driven fertilization strategy is mainly due to the degree of openness in the recirculation system of the nutrient/drainage-solution. In closed systems, all nutrients stay within the production system in virtue of the complete recirculation of the nutrient solution, and in this respect do not leach. However, due to the accumulation of some nutrients, especially sodium and chloride, the nutrient solution becomes useless over time, and must be disposed of at a certain frequency (Breś 2009, Breś and Trelka 2015). The frequency of the disposal depends on factors such as water quality and composition of the desired nutrient solution, which in turn depends on geography and type of production system. The losses through disposal are small, as they can be reduced up to 65%, compared to an open fertigation system (Breś 2009). Fertigation in closed systems is especially used in soilless plant production, but it is not possible to completely eliminate losses even in this case (Breś 2009).

However, there are many examples of intense greenhouse production with relatively high leaching losses, which leads to environmental pollution (Breś 2009) reported for many countries, such as Spain, Italy, Morocco (Cuervo *at al*. 2012, Pardossi *et al.* 2004), Northern Ireland (Jordan *et al*. 2005), Sweden (Hansson 2003), Turkey (Merica 20011), China (Hu at al. 2012, Min *et al*. 2011) and Colombia (Cuervo *et al*. 20120). In these cases, systems are open, and the suggested solution is to close them in order to recirculate the nutrients (Breś and Trelka 2015).

Fertigation according to plant demand

A third way to employ fertigation is to apply the fertilizer based on the crop demand. This is an unnoticed and little used strategy, which potentially could decrease nutrient leaching. It was developed at SLU by a research group led by Torsten Ingestad. Ingestad and coworkers focused on the physiological nutrient need of plants, and application methods.

Ingestad and coworkers established a concept about ratios of essential nutrients needed by plants during growth, being similar for all terrestrial plants (Ericsson 2006), as displayed in Table 1. Furthermore, Ingestad and coworkers created a mechanistic and mathematical theory that explained the relation between nutrients, growth and allocation of resources, from which they in turn made an intuitive fertilizer application model (Ericsson 2006, Ingestad 1982, 1988, Ingestad and Ågren 1992). The theory has high predictive power with high accuracy, even for simplified

Table 1. Nutrient requirements of plants given in nitrogen ratios[a], at steady state and maximum growth

Macronutrient	Ratio to N	Micronutrient	Ratio to N
Nitrogen (N)	100	Iron (Fe)	0,7
Phosphorus (P)	13-19	Manganese (Mn)	0,4
Potassium (K)	45-80	Boron (B)	0,2
Sulfur (S)	8 - 9	Zink (Zn)	0,06
Magnesium (Mg)	5 - 15	Copper (Cu)	0,03
Calcium (Ca)	5 - 15	Chloride (Cl)	0,03
		Molybdenum (Mo)	0,003

[a] the ratios are based on the mass relation between each element divided by the mass of nitrogen. The ratios are then multiplied by 100 in order to present them as percentages.

systems (Ingestad 1982, 1988, Ingestad and Ågren 1992, Rytter et al. 2003). The research of Ingestad and coworkers was based and extensive laboratory and field work over a long period of time (Nachmansohn 2004).

Fertilizer application model

Ingestads model for application of nutrients is based on the momentary demand of the plant. Nutrients are applied in accordance with a sigmoid plant growth curve and adjusted to the nutrient delivery capacity of the growth medium. As such the model provides a low supply rate in the beginning of the growth season that increases exponentially over time until the plant has its maximum growth rate. Thereafter the supply rate decreases exponentially until the end of the growth season. For a more detailed expansion of Ingestads model see the appendix.

Low leaching

Several examples have been reported where the plant demand-driven fertilization strategy of Ingestad resulted in higher nutrient use efficiency, similar or higher yield levels and less leaching than conventional fertilization strategies (Ingestad 1982, Kätterer and Andrén 1996, Kätterer *et al.* 1997, Rytter et al. 2003). Leaching depends on how precise nutrients can be supplied to the production system. Micro-irrigation and recirculation of nutrient solution according to the Ingestad model can provide high precision, which virtually leads to no losses, as plant uptake of added N is almost 100 % (Ingestad 1977, T. Ericsson, Swedish University of Agricultural Sciences, personal communication). Consequently, leaching of added N is negligible. Even for less precise systems, with more generous irrigation and lower frequency of nutrient input, leaching losses are still low without reducing yields (Rytter et al. 2003).

The limitations of fertigation

All methods based on fertigation depend on an irrigation system. Thus, it is limited to production systems that already have irrigation or systems where the economical or logistical circumstances justify such a heavy investment. The method could likely be applied successfully in most of the arid and semi-arid farmland in the world as long as it can be provided with proper irrigation. In Sweden and the rest of northern Europe or America, the method is not viable in open-field plant production, and virtually only employable in green-house production, intensive horticultural fields and gardening.

Aims and objectives

The objective of this paper is to compare different fertilization strategies with regard to the risk for nutrient losses. Demand-driven fertilization according to Ingestad will be tested experimentally and compared with conventional nutrient supply strategies. The nutrient in focus in this thesis is nitrogen, especially in the experiment, but phosphorus will also be assessed to a lesser extent.

Materials and methods

Experimental setup

The green-house study was carried out as a fully randomized pot experiment at the SLU in Ultuna, Uppsala in the BioCenter greenhouse. The pots used were VEFI PF 310 plastic pots (Econova Garden AB, Åby, Sweden), each with a volume of 0.55 l, a height of 7.5 cm and a square opening with a side of 10.5 cm. The growing area for the experimental treatment was 2.4 m^2 and the number of pots was 90.

The growth substrate was a mixture of 92 % pure sand and 8 % of a peaty commercial plant soil which was thoroughly homogenized before placement in the pots. The sand had an average particle size of 0.50 mm and a maximum particle size of 1.40 mm (Rådasand AB, Lidköping Sweden). The plant soil was S-jord which is gently pre-fertilized and contains 94 % finely divided peat and 6 % perlite (Hasselfors Garden, Örebro, Sweden). To avoid impact from the pre-added fertilizers in the experiment, the peat soil was rinsed a couple of times with tap water and finally with de-ionized water. The experimental crop was sunflower.

Treatments

Four different fertilizing strategies plus one blank were compared in an experiment that lasted for 57 days:

1. *Demand-driven* strategy: fertilization according to Ingestad and coworkers, at a rate intended to supply the plant with its nutritional needs at any point in time, thus to avoid nutrient and growth limitations. The fertilization scheme in this treatment was based on data on growth pattern and nutrient demand of sunflower from prior research and

experience of Ingestad and coworkers, and Tom Ericsson, a member of the former Ingestad team was consulted for that purpose. An exponential growth with an increase of 8% fresh weight per day for the whole treatment period was estimated. This estimation is well founded on previously recorded maximum growth rate; however, it is a slight underestimation. This was done consciously, in order to safeguard against overdoses of nutrients at the end of the fertilizer program. With an exponential addition rate there is always a risk if the growth is overestimated just the slightest. A young sunflower seedling that weighs 1 g contains 6 mg N g^{-1} fresh weight; this fact combined with the known maximum growth rate made it possible to calculate the maximum total demand of N for the whole growth period to 189 mg. The amounts of the other nutrients were added in accordance with Ingestads theory as proportions of total N (as shown in Table 2). The nutrient solution used was Blomstra (Cederroth International AB, Falun, Sweden) which depart minimally from the recommended ratios according to Ingestad as it is based on his research. The differences are negligible and are due to commercial considerations by the manufacturer (compare Table 1 and 3). The supply rate follows the estimated growth curve exactly and is distributed daily. The nutrient supply followed an accumulative exponential curve (see Figure 1), and is given by the following function, where F is the daily dose on day *t*:

$$F(t) = C(t) - C(t-1) \qquad \text{(Equation 1)}$$

where *t* = the number of days since fertilization began and C is the nutrient content in the plant on day *t* if there is no nutrient limitation, which is given by:

$$C(t) = C_0\, e^{RG\, t} \qquad \text{(Equation 2)}$$

where t = the number of days since fertilization began and C_0 = is the nutrient content in the plant on day *t* = 0 and RG is the relative growth rate and was estimated to 0.08.

2. *Linear* strategy: conventionally used in greenhouse production with the intention to supply the plants with an approximate constant flux of nutrients (amounts of nutrients per unit of time). In this treatment the concentrations of the nutrients in the soil solution is held at a constant level in line with conventional understanding of the specific nutrient requirements of the crop culture. In this treatment the total N supplied was the same as in strategy number 1, i.e. 189 mg. The fertilizer Vitagro (Bayer AB, Staffanstorp, Sweden), commonly used for universal production of flowers and fruits in greenhouses and gardens was chosen as representative for this strategy (Table 2). The conventional understanding of desired fertilizer composition is explained and discussed thoroughly by Nachmansohn (2014). Vitagro does not contain all essential nutrients, however, due to the short

cultivation period and the expected complementary nutrient delivery from the soil, this shortage is usually considered to be of negligible effect. However, as the experiment proceeded I decided to ensure that the plants were given a sufficient amount of S. Therefore, the plants were given potassium sulfate (K_2SO_4) in a solution with a concentration slightly above 0.5 g K_2SO_4 per liter de-ionized water, as a onetime dose of roughly 50 ml at day 33. The supply rate is constant (see Figure 1), thus the dose is constant and applied daily. The dose F is calculated from the following equation:

$$F = t^{-}{}_{(max)}{}^{-1}\ C_0\, e^{RG\ t(max)} \qquad \text{(Equation 3)}$$

where $t_{(max)}$ is the last day within the interval $1 \leq t \leq 57$

3. *Predetermined* strategy: conventional supply with approximately constant, pre-determined amounts of nutrients per unit time. This method of nutrient addition has been, and still is, commonly used in horticulture and Swedish forest nurseries (T. Ericsson, Swedish University of Agricultural sciences, personal communication, Rytter *et al.* 2003). This treatment is similar to strategy number 2, and deviates only in two respects: firstly, the total amount of N in this treatment was 227 mg, which is 20 percent more than in strategies 1 and 2. This increase in fertilizer was done in order to reflect the total amount commonly used in conventional production. This is contrasted by the total amount in treatment 1 and 2. The supply rate is every second or third day according to a pre-determined pattern, simulating fertilization twice a week instead of once a day. The treatment period of 57 days is approximately 8 weeks; hence there were 16 instances of fertilization. Thus the dose F was the same at all fertilization occasions and is given by the function:

   $$F = 16^{-1}\ 1.2\ C_0\, e^{RG\ t(max)} \qquad \text{(Equation 4)}$$

   where $t_{(max)}$ is the last day within the interval $1 \leq t \leq 57$

4. *Onetime application* strategy: conventional fertilizer supplied at the start of the growing season. This treatment is meant to simulate the practice of supplying all fertilizer prior to, or at sowing. This practice is common in most areas of plant production, horticulture as well as agriculture. In this treatment the total N was the same as for the strategy number 3, i.e. 227 mg. In this treatment the solid fertilizer Weibulls Trädgårdsgödsel mineral (Econova Garden AB, Åby, Sweden), was chosen for the same purpose as in strategies number 2 and 3, that it represents a composition of fertilizers used in conventional production. The treatment was meant to be executed on day $t = 1$, but due to practical problems it was delayed to day $t = 2$. The dose F is given by the function:

$F = 1.2\ C_0\ e^{RG\ t(max)}$ (**Equation 5**)

where $t_{(max)}$ is the last day within the interval $1 \leq t \leq 57$

5. *Blank*: control treatment without any fertilizer application. In all other respects this treatment is the same as treatment 1-4. This treatment serves as a reference to above treatments, but also as a measure of the nutrient delivery capacity of the soil.

Implementation of experiment

Sunflower seeds (commercial birdseed) was sown in mid Mars in 2015 and covered with approximately 1cm soil. In order to allow the seedlings to grow big enough for treatment they were grown with irrigation without fertilization until they reached an average weight of 0.33 g. Then the seedlings were grown for 57 days under treatment. Irrigation was performed daily in all treatments throughout the whole period with a few exceptions. However, later during the experiment the demand increased and the plants were watered approximately twice a day. Irrigation amounted up to approximately 100 ml per pot and occasion, varying somewhat between treatments, because of differences in demand.

Nutrient and water application

The liquid fertilizers as well as the solid fertilizer had the concentrations and proportions of the essential elements shown in Table 2. The nutrient solutions added to the pots were obtained by diluting the original liquid fertilizers with a factor of hundred. The nutrient solutions or pure water in treatment 4 were spread over the soil surface by hand with micropipettes. The solid fertilizer was mixed into the soil approximately 2-3 cm below soil surface in a ring around the

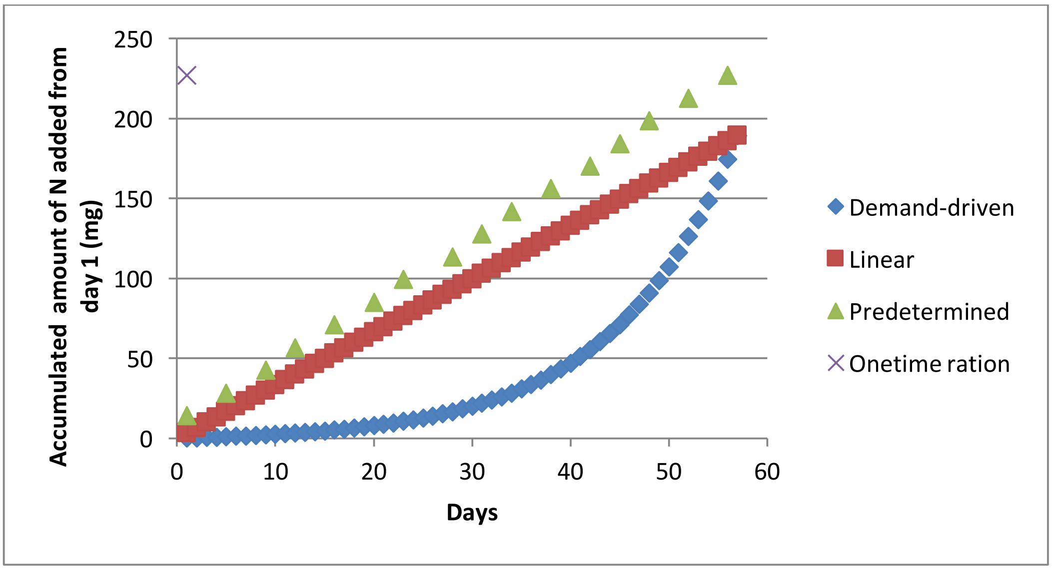

Figure 1. Accumulated amount of nitrogen added in all strategies in the experiment over the growth period.

seedlings. The amounts of water applied were controlled to milliliter precision with measuring glasses. Water purified by softening, reverse osmosis and electro-deionization, with conductivity below 1 mS cm^{-1}, was used.

In the greenhouse the plants were grown in the center area on a cultivation table that was covered with a plastic film. The table was located approximately in the center of the room in the greenhouse. Within the area used, the positions of the pots were random and rotated during the growth in order to rule out any spatial variation in light and other factors regulating growth. For practical reasons all pots for each treatment were placed next to each other. Due to renovation of the greenhouse the pots were transferred to a room next door for 10 days. All rooms in the greenhouse are virtually identical and the pots had the same position in this room.

Sampling and analysis of drainage water

On five occasions, leaching was simulated in all treatments, by flushing de-ionized water through the pots and collecting excess drainage water. Each replicate consisted of three pots with one plant in each, and was measured by collecting an equal amount of leachate water from its

Table 2. Concentrations of elements in fertilizers used in demand-driven[a], linear[b], predetermined[b] and onetime application[c] strategy.

Element	Demand-driven	Linear & Predetermined	Onetime Application
	(g l^{-1})	(g l^{-1})	(g kg^{-1})
Nitrogen (N)	51	58	9.0
Nitrate	20	-	3.4
Ammonium	31	-	5.6
Phosphorus (P)	10	12	4.6
Potassium (K)	43	46	14.1
Sulphur (S)	4	-	10.0
Calcium (Ca)	3	-	-
Magnesium (Mg)	4	0.68	1.6
Iron (Fe)	0.17	0.39	0.2
Manganese (Mn)	0.20	0.13	0.25
Boron (B)	0.10	0.023	0.05
Zink (Zn)	0.03	0.052	0.04
Copper (Cu)	0.015	0.059	0.03
Molybdenum (Mo)	0.0004	0.014	0.002
Cobalt (Co)[d]	-	-	0.002

[a] Liquid fertilizer: Blomstra 51-10-43+micro. The density of the fertilizer solution at 20° C is 1.144 kg^{-1} l. [b] Liquid fertilizer: Vitagro 5-1-4+micro. The density of the fertilizer solution at 20° C is 1.152 kg^{-1} l. [c] Solid fertilizer: Weibulls Trädgårdsgödsel mineral. [d] Co is not a plant nutrient per see, but feed for benevolent microbes.

three pots and merge them into one sample and analyze the content. The collected water was quantified and analyzed for total N and P content by the geochemical laboratory at the Department of Aquatic Sciences and Assessment, SLU, according to their standard procedure (Swedish University of Agricultural Sciences 2015). The aim of the first leaching simulation was to let 100 ml pass through the pots, but due to practical problems approximately 120 ml water was collected on average. The aim at the second simulation was also 100 ml, and the second time the collected water was approximately 100 ml in average. The three last simulations were performed under higher precision and were measured more carefully. The collected excess drainage water for the three last simulations was approximately 50 ml. 100 ml of water is the equivalent of 20 mm rain if spread over the surface of the pot. The aim was to calibrate the leaching simulations with the results from the first simulation. However, I received the results for the first leaching simulation, after the second simulation was performed, which means that the calibration was done before the last three simulations. Then it was discovered that 100 ml was a little excessive, which is the reason why I choose to go down to 50 ml per simulation and ensure higher precision.

The simulation of leaching made it necessary to grow the plants in pots with drainage holes that release excess water. This meant a risk for uncontrolled water and nutrient losses from the daily irrigation, if excess water with nutrients wasn't returned to the pot. For practical and economic reasons, the pots were placed in sets in common containers for the first 30 days, which made it

Table 3. Supply of nutrients in the different treatments expressed as mass relations to nitrogen input (in percent). Note that the data in column Demand-driven depart minimally from those in Table 1 due to the composition of Blomstra.

Element	Demand-driven	Linear & Predetermined	Onetime application
Nitrogen (N)	100	100	100
Phosphorus (P)	20	21	51
Potassium (K)	84	79	157
Sulphur (S)	8	-	111
Magnesium (Mg)	8	1	18
Calcium (Ca)	6	-	-
Iron (Fe)	0.3	0.7	2
Manganese (Mn)	0.4	0.2	3
Boron (B)	0.2	0.04	0.6
Zink (Zn)	0.06	0.09	0.4
Copper (Cu)	0.03	0.1	0.3
Chloride (Cl)	-	-	-
Molybdenum (Mo)	0.0008	0.02	0.02
Cobalt (Co)	-	-	0.02

impossible to control what happened with excess water eventually leaving the pots. The pots were placed in containers in sets of initially 15, and as the plants grew in sets of 8, 7 and 6 in order to meet the increasing need for wider space between them when plants grew bigger. During this phase the plants were irrigated carefully in order to prevent any losses of water and nutrients. However, during the implementation of the experiment small and presumably negligible losses were documented on a few occasions. The last 27 days the pots were placed on individual plates, and during this phase the irrigation was more generous in order to ensure that the plants were supplied with enough water, as excess water with nutrients would return to the pot.

Sampling and analysis of plants

Plants were sampled to determine biomass and nutrient content. In total there were three sampling occasions. The first samples were taken approximately halfway through the treatment (day 26) due to the short growth period, and then systematically approximately every second week (day 40 and 58). Each treatment had two replicates, which in turn was made up by three pots with one sunflower plant in each pot. The plants from these three pots were merged to one sample before analysis. Thus, in total, 90 pots with one sunflower in each at the beginning of the experiment. Each pot was randomly chosen and tagged with its specific treatment, replicate number and predetermined sampling occasion before starting the experiment. Thus, on each sampling occasion 30 plants were sampled and they represented two replicates from each treatment. The sampling was performed as follows: the above ground fresh biomass was cut off and weighted, and the below ground biomass was separated from the soil. The roots were carefully separated from the soil, by submerging the remaining content of the pot into de-ionized water and then gently massaging it until all soil was removed, to avoid losses of below ground biomass. The plant fractions were dried at 70 C° to constant weight for 2-3 days before dry weight (DW) determinations. N and P in plant fractions were analyzed with an elemental analyzer at the Plant Nutrient laboratory, Department of Soil and Environment, SLU.

Statistics

The statistical analysis was performed as one-way ANOVA-tests, in which the mean values were compared with the Tukey method and 95% confidence level. The analysis was done in Minitab 17 (Minitab Inc., State College, Pennsylvania, USA). Data analysis was made separately for each occasion of rain simulation or harvest.

Due to sampling of plants throughout the experiment, and removal of the sampled extra replicates as the experiment continued, the number of leachate samples decreased with time. Thus the first simulation of leaching had six data points, the second and the third had four data points, and the fourth and the fifth had two data points. In order to get equal weight of data from different sampling occasions in the statistical analysis, the data from simulation 1, 2 and 3 was averaged to two data points. This applies to statistical analysis of means, sums and accumulated leaching from the rain simulations.

In some cases, treatment number 4 (onetime application), gave outlying results. Sometimes it had much higher mean values than the other treatments, which led to ANOVA-results where the Tukey comparison gave that only treatment number 4 was significantly different. At one occasion treatment number 4 had both much higher mean value and extreme variance compared to other treatments. In all these cases the treatment number 4 disturbed the ANOVA-test, and was therefore excluded. It was obvious in all these cases that treatment number 4 had significantly higher values.

Results & Discussion

Nitrogen

Leaching from rain simulations

Nitrogen is the primary element in this study, and is examined in all leaching simulations and harvests.

N drained in the leaching simulations is presented in Table 4. These results are very straightforward. Over-all demand-driven strategy leaches the least and the onetime application strategy leaches the most, and linear and pre-determined supplies are similar, though the linear strategy leaches a little less.

The demand-driven strategy leached least of all leaching simulations except the last one, in which it leached the most. Still, in leaching simulation 5, the difference in leaching between the demand-driven strategy and the other strategies is small, considering that so much more N is

Table 4. Amount of nitrogen in drainage water in leaching simulations. Means of 2-6 [a] replicates. Means in vertical columns that do not share the same letter[b] are significantly different.

	Leaching simulation					
	1^{c}	2^{c}	3^{c}	4	5	SUM^{c}
Strategy	**Tot-N leached/pot (µg)**					
(5) Blank	547^{A}	304^{A}	150^{A}	126^{A}	136^{A}	1263^{A}
(1) Demand-driven	381^{A}	303^{A}	134^{A}	188$^{A C}$	749^{B}	1754^{A}
(2) Linear	1685^{B}	837^{B}	306^{B}	344^{B}	445^{C}	3617^{B}
(3) Predetermined	3672^{C}	833^{B}	405^{C}	356^{B}	495^{C}	5761^{C}
(4) Onetime application	129’000	28’000	2186	247^{C}	246^{D}	16’000
[a] number of observations	n=6	n=4	n=4	n=2	n=2	n=2

[b] Tukey Method and 95% Confidence interval. [c] in these vertical columns the very high values in strategy (4) disturbed the ANOVA-test; thus it was excluded from the test. For detailed information, see the heading Statistics.

added, in both amount and frequency, for the demand-driven strategy during the last time of the experiment (compare the difference in total added N for each strategy in Figure 1 between day 42 and day 55). Furthermore, the weather was better for plant production in the first part of the growth period than in the latter, especially if the growth potential of the crop is considered. The plants with linear and pre-determined fertilization had N excess during approximately the first two thirds of the experiment, despite the large losses in the artificial leaching (compare the slopes for the strategies in Figure 1), and had grown bigger than plants with demand-driven fertilization. Bigger plants mean larger uptake capacity. Furthermore, it should be pointed out that the leaching in simulation 5 was less than 1 mg for all strategies. In summary, even though the demand-driven fertilization leached the most in simulation number 5, it leached less in total considering the amount of N supplied, which indicates that the method has the potential for preventing leaching.

Another observation is that the demand-driven strategy and the blank are not significantly different at any simulation except the last one. It doesn't matter if it is the concentration or total amount leached N. This implies that the N-demand of the plants are met and that all N added are taken up quickly, and that the N found in leachates are explained by the background N found in the soil. Furthermore, in the first three leaching simulations, the demand-driven strategy actually leaches less than the blank, which could be explained by increased uptake capacity of the plants due to growth promotion from the fertilization. In other words: the plants in the blank wasn't big enough to take up the N in the soil, while the plants in the demand-driven had a well developed root system due to its growth patterns. This difference is not statistically significant, but if it could be shown to be so in reality through further research, it would mean that the demand-driven strategy leads to lower leaching than that of the background.

The onetime application strategy leached very much in the beginning and very little in the end. This presumably mainly has two reasons:
(1) all N was added at the beginning and much of it leached during the two first leaching simulations. Furthermore, the two first leaching simulations were excessive, partly due to an overestimation of how much water that was to be added, and partly due to problems with calibration, as mentioned under the heading Sampling and analysis of drainage water. Thus a fairly large amount of the added N was lost at an early stage. It is possible that this is also partly true for the linear and pre-determined strategy, since the supply rate of N was higher than growth rate in the beginning of the experiment.
(2) at the end of the experiment the plants had grown relatively big due to the high initial N application, and had a large enough uptake capacity to take up most of the remaining N.

So basically, N that didn't leach at an early stage was taken up by the plants later before rain simulation 4. Thus, the latter rain simulations leached very little, as little N was still mobile in the pots.

Uptake

The accumulated N uptake varies over time between the different treatments, but in harvest 3 demand-driven, linear and pre-determined are equally high, while the onetime application is considerably lower. Over all harvests the N uptake in per cent of added amount is highest for the demand-driven strategy and lowest for the onetime application, the linear and pre-determined are relatively similar. The accumulated leaching up until each harvest is smallest for the demand-driven strategy and largest for the onetime application, the linear and pre-determined are relatively similar, but predetermined leached significantly more. (Table 5-7)

At the first harvest (see Table 5) the N uptake exceeds added N in the demand-driven strategy, indicating that this strategy uses more soil N at this stage. The other strategies do that to a lesser extent due surplus input of N.

At the second harvest (Table 6) the accumulated total uptake is significantly lower for demand-driven compared to the other three treatments, which in turn are not significantly different from each other. This seems to be the case due to higher N input in treatment 2-4, since the demand-driven has considerably lower leaching and higher accumulated uptake in per cent of added N. Leaching for demand-driven is not significantly different from that in the blank, but the accumulated uptake has decreased from 100 to 88 per cent compared to the first harvest (Table 5 and 6). It is also notable that the onetime application has increased in accumulated uptake from 21 to 41 per cent.

Harvest 1

Table 5. Accumulated uptake of nitrogen, compared to added and leached nitrogen. Means of 2 replicates. Means in vertical columns that do not share the same letter[a] are significantly different.

Harvest 1 Day 26 of 58	**Accumulated uptake**	**Accumulated N addition**	**Accumulated uptake**	**Accumulated Leaching[b]**	**Residual[c] N**
Strategy	**(mg/plant)**	**(mg/pot)**	**% of added N**	**(mg/pot)**	**(mg/pot)**
(5) Blank	5,4^{A}	0,0	-	0,55^{A}	-6,0
(1) Demand-driven	18$^{A\ C}$	13	100	0,38^{A}	-5,7
(2) Linear	58^{B}	83	70	1,7^{B}	23
(3) Pre-determined	61^{B}	99	62	3,7^{C}	35
(4) Onetime application	48$^{B\ C}$	227	21	129	50

[a] Tukey Method and 95% Confidence interval. [b] in this vertical columns the very high values in strategy (4) disturbed the ANOVA-test; thus it was excluded from the test. For detailed information, see the heading statistics.
[c] added N minus both accumulated uptake and accumulated leaching of N.

Harvest 2

Table 6. Accumulated uptake of nitrogen, compared to added and leached nitrogen. Means of 2 replicates. Means in vertical columns that do not share the same letter[a] are significantly different.

Harvest 2 Day 40 of 58	**Accumulated uptake**	**Accumulated N addition**	**Accumulated uptake**	**Accumulated Leaching**[b]	**Residual**[c] **N**
Strategy	**(mg/plant)**	**(mg/pot)**	**% of added N**	**(mg/pot)**	**(mg/pot)**
(5) Blank	7,7$^{\underline{A}}$	0,0	-	1,0$^{\underline{A}}$	-8,7
(1) Demand-driven	41$^{\underline{B}}$	47	88	0,82$^{\underline{A}}$	4,9
(2) Linear	98$^{\underline{C}}$	133	74	2,8$^{\underline{B}}$	32
(3) Pre-determined	113$^{\underline{C}}$	156	73	4,9$^{\underline{C}}$	38
(4) Onetime application	113$^{\underline{C}}$	277	41	159	4,4

[a] Tukey Method and 95% Confidence interval. [b] in this vertical columns the very high values in strategy (4) disturbed the ANOVA-test; thus it was excluded from the test. For detailed information, see the heading statistics.
[c] added N minus both accumulated uptake and accumulated leaching of N.

At harvest 3 (see Table 7) there is no significant difference in the accumulated uptake between demand-driven, linear and predetermined strategy, which indicates that these methods leads to the same total uptake in the end. However, the total N uptake in the demand-driven strategy is virtually the same as for pre-determined strategy, despite that the latter had been given 20 % more N at that time. It should also be noted that all harvests are independent trials, which explains how the accumulated uptake for the onetime application can be lower in harvest 3 than in harvest 2 (Table 6-7). The difference in uptake indicates that the onetime application may lead to more variable results.

What is not clear is the fate of the residual N (see Table 5-7). Presumably some is adsorbed to the organic material of the soil, some remain in the soil solution in the pots and some is lost through gaseous emissions upon denitrification. Also due to the human factor, error occurs in the

Harvest 3

Table 7. Accumulated uptake of nitrogen, compared to added and leached nitrogen. Means of 2 replicates. Means in vertical columns that do not share the same letter[a] are significantly different.

Harvest 3 **Day 58 of 58**	**Accumulated uptake**	**Accumulated N addition**	**Accumulated uptake**	**Accumulated Leaching**[b]	**Residual**[c] **N**
Strategy	**(mg/plant)**	**(mg/pot)**	**% of added N**	**(mg/pot)**	**(mg/pot)**
(5) Blank	5,0$^{\underline{A}}$	0,0	-	1,3$^{\underline{A}}$	-6,2
(1) Demand-driven	162$^{\underline{B}}$	189	85	1,8$^{\underline{A}}$	26
(2) Linear	145$^{\underline{B}}$	189	77	3,6$^{\underline{B}}$	40
(3) Pre-determined	163$^{\underline{B}}$	227	72	5,8$^{\underline{C}}$	59
(4) Onetime application	77$^{\underline{C}}$	227	34	160	-10

[a] Tukey Method and 95% Confidence interval. [b] in this vertical columns the very high values in strategy (4) disturbed the ANOVA-test; thus it was excluded from the test. For detailed information, see the heading statistics.
[c] added N minus both accumulated uptake and accumulated leaching of N.

implementation of a methodology. Accidental leaching that didn't return into the pots or wasn't collected for quantification could explain, at least in part, why the posts of remaining N was so big for the linear and pre-determined strategies in all harvest, and perhaps also for the demand-driven strategy in the last harvest.

Growth and plant N concentration

At a quick glance it is clear that for most part there is no significant difference between the treatments, especially at harvest 3 (Table 8). However, linear and pre-determined strategies resulted in highest plant growth at all harvests and were similar throughout the experiment, while demand-driven had lower at harvest 2, and onetime application had lower at harvest 1.

The onetime application treatment is very interesting. At harvest 1 the onetime application strategy showed least growth despite highest fertilizer dose. This is presumably due to high soil salinity caused by to too high fertilizer input, which inhibits growth. At harvest 2 it has caught up with the linear and pre-determined strategy, which could indicate that soil salinity was mitigated by the high leaching, but in the last harvest it is on last place again and seems to stagnate in growth. This could be explained by the fact that when the plant overcame growth inhibition it had high internal concentrations of nutrients that enabled high growth rate, but later on the growth stagnated, due to a high nutrient loss through leaching, and slow growth at the start. Basically, this strategy either had detrimental or insufficient levels of nutrients for most of the growth period. However, this cannot be extrapolated to open field production, where the soil volume isn't limited to a small pot. Presumably under field conditions, the same salinity levels would not be reached. (Table 8)

The concentration of plant N is stable for demand-driven strategy throughout the experiment, and also has the highest concentration of plant N of all treatments at the end of the experiment (Table 9). The onetime application has the highest concentration of all treatments in the beginning and very low at the end. Linear and predetermined have high internal concentration at the beginning which decreases throughout the experiment. The onetime application has very high concentration in the beginning but then follows a pattern similar to treatment 2 and 3.

Table 8. Total plant dry biomass according to each strategy at the point of each harvest. Means of 2 replicates. Means in vertical columns that do not share the same letter[a] are significantly different.

Total dry biomass of plants	**Harvest 1**	**Harvest 2**	**Harvest 3**
Strategy	**Total dry biomass (g)**		
(5) Blank	0,66^{A}	1,6^{A}	1,3^{A}
(1) Demand-driven	1,5$^{A B}$	3,2^{A}	13$^{A B}$
(2) Linear	2,4^{B}	9,5^{B}	21^{B}
(3) Pre-determined	2,2^{B}	9,9^{B}	20^{B}
(4) Onetime application	1,1^{A}	8,3^{B}	11$^{A B}$

[a] grouping information using the Tukey Method and 95% Confidence interval.

Table 9. Average concentration of N in total plant biomass for each strategy. Means of 2 replicates. Means in vertical columns that do not share the same letter[a] are significantly different.

Internal concentration of N	**Harvest 1**	**Harvest 2**	**Harvest 3**
Strategy		**Tot-N, % of total biomass**	
(5) Blank	0,83$^{\underline{A}}$	0,48$^{\underline{A}}$	0,39$^{\underline{A}}$
(1) Demand-driven	1,3$^{\underline{B}}$	1,3$^{\underline{B\ C}}$	1,3$^{\underline{B}}$
(2) Linear	2,5$^{\underline{C}}$	1,0$^{\underline{D}}$	0,71$^{\underline{C}}$
(3) Pre-determined	2,8$^{\underline{D}}$	1,2$^{\underline{B\ D}}$	0,82$^{\underline{C}}$
(4) Onetime application	4,5$^{\underline{E}}$	1,4$^{\underline{C}}$	0,72$^{\underline{C}}$

[a] Tukey Method and 95% confidence interval.

To understand the results for growth and plant N concentration two things must be kept in mind:
(1) the experiment did not comprise a whole growth season, due to the limits of the framework for a master's thesis. Therefore, the treatments could not reach its full potentials or final outcomes at the end of a growth period.
(2) the weather was, as mentioned before, more growth promoting in the first part of the experiment than in the latter part, and since bigger plants have greater growth capacity than smaller, plants that grew bigger in the beginning of the experiment had an advantage in this case.

It seems reasonable to expect the demand-driven strategy to have a slow start, and thus problems to initially catch up in growth compared to the linear and pre-determined strategy. If so, the demand-driven strategy probably would have caught up, if the experiment had lasted for a whole growth season. The following points in that direction:
(1) The plant N concentration (Table 9) in the demand-driven is very stable throughout the whole experiment, which implies a stable relative growth rate for the demand-driven strategy, i.e. a stable exponential growth. For linear and pre-determined strategies plant N are decreasing throughout the experiment, which implies a continuous decrease in the relative growth rate over time.
(2) The increase in total dry biomass over time could only match an exponential curve for the demand-driven strategy (see Table 8).

Phosphorus

Leaching

Phosphorus is the second element in this study. It is analyzed in all leaching simulations, but in contrast to nitrogen it is only analyzed in one harvest; the last one.

P leaching is presented in Table 10. Over-all demand-driven strategy leaches the least and the onetime application strategy leaches the most, and linear and pre-determined supply showed little difference between them. The demand-driven strategy leached most of its P in the last

Table 10. Amount of phosphorus in drainage water at leaching simulations. Means of 2^{a} replicates. Means in vertical columns that do not share the same letter^{a} are significantly different.

	Rain simulation					
	1^{c}	2^{c}	3^{c}	4	5	SUM^{c}
Strategy	Tot-P leached/pot (µg)					
(5) Blank	276^{A}	143^{A}	54^{A}	38^{A}	29^{A}	541^{A}
(1) Demand-driven	237^{A}	87^{A}	31^{A}	30^{A}	203^{B}	588^{A}
(2) Linear	522^{B}	257^{B}	44^{A}	34^{A}	31^{A}	888^{A}
(3) Predetermined	772^{C}	380^{C}	122^{B}	50^{A}	43^{A}	1367^{B}
(4) Onetime application	34’000	12’000	5293	2243^{B}	359^{C}	53’000
^{a} number of observations	n=6	n=4	n=4	n=2	n=2	n=2

[b] Tukey Method and 95% Confidence interval. [c] in these vertical columns the very high values in strategy (4) disturbed the ANOVA-test; thus it was excluded from the test. For detailed information, see the heading statistics.

leaching simulation, just as it did with N. This is probably due to the same reasons as for why it leached the most N, i.e. high fertilizer addition rate at the time of the simulation.

Plant uptake

The accumulated uptake is very similar for all strategies in terms of mg/plant. However, the accumulated uptake in terms of per cent of added P is considerably lower for the onetime application compared to the other strategies, which are similar (Table 11). Furthermore, the residual P is high for all strategies compared to the input, especially for the onetime application.

A major difference between P and N is that P is more easily adsorbed to the particle surfaces in the soil, which complicates its dynamics in the soil. Adsorbed P can be the main part of the residual P after leaching and uptake (see Table 11), but it is hard to know, it could also be accidental leaching undetected by measurements. These results imply that demand-driven and linear best prevents leaching and residues in the soil.

Table 11. Accumulated uptake of phosphorus, compared to added and leached phosphorus. Means of 2 replicates. Means in vertical columns that do not share the same letter^{a} are significantly different.

Harvest 3 Day 58 of 58	Accumulated uptake	Accumulated P addition	Accumulated uptake	Accumulated Leaching^{b}	Residual^{c} P
Strategy	(mg/plant)	(mg/pot)	% of added P	(mg/pot)	(mg/pot)
(5) Blank	3,0^{A}	0,0	-	0,54^{A}	-3,5
(1) Demand-driven	30$^{A\ B}$	38	78	0,59^{A}	7,6
(2) Linear	31$^{B\ C}$	40	79	0,89^{A}	7,4
(3) Pre-determined	34^{C}	48	71	1,4^{B}	12
(4) Onetime application	30^{B}	116	26	53	33

[a] Tukey Method and 95% Confidence interval. [b] in this vertical columns the very high values in strategy (4) disturbed the ANOVA-test; thus it was excluded from the test. For detailed information, see the heading statistics.
[c] added P minus accumulated uptake and accumulated leaching of P.

Table 12. Concentration of N in total plant biomass for each strategy. Means of 2 replicates. Means in vertical columns that do not share the same letter[a] are significantly different.

Harvest 3 Day 58 of 58	Total dry biomass of plants	Internal concentration of P
Strategy	**Total dry biomass (g)**	**Tot-P % of total biomass**
(5) Blank	1,3^{A}	0,23$^{A\ B}$
(1) Demand-driven	13$^{A\ B}$	0,23^{B}
(2) Linear	21^{B}	0,15$^{A\ B}$
(3) Pre-determined	20^{B}	0,17^{A}
(4) Onetime application	11$^{A\ B}$	0,28$^{A\ B}$

[a] Tukey Method and 95% Confidence interval.

Growth and plant P concentration

The concentration of plant P is similar for all strategies. The total dry matter biomass is the same as presented before, and in comparison to plant P concentrations it is hard to see a relation between growth and concentration of plant P. (Table 12)

These results are more difficult to interpret than to those for N for at least two reasons. First, the plant P concentrations are similar for all strategies, and thus may have influenced the growth patterns similarly in all treatments. The differences in growth rate in this study seem more to be controlled by the N input.

Experiment vs reality

How much does the experiment reflect reality? Overall, the different results (leaching, plant uptake, growth and plant nutrient concentration) are coherent. However, experimental conditions did not represent normal growth conditions. First, the pots were very small limiting root growth, and the leached nutrients were lost early at the start of the experiment. In field conditions, the leachates are not necessarily lost upon fertilization but either remains in soil or at least in part return to the root zone through the predominant upward water movement during the growth season. This is particularly true in dry climates. Furthermore, as mentioned before, the two first rain simulations were excessive and are probably more representative for extreme rains than heavy rains. Still, the experiment reflects the principles at work in real plant production and shows how the different fertilization strategies relate to each other in a qualitative sense.

Comparing theoretical models with empiricism

The demand-driven method of Ingestad and coworkers differs from the other strategies in several respects.

Firstly, the demand-driven method is based on the physiological nutrient need of the plant, while the other methods often are empirically based. Of course also the latter strategies are founded on theories on how soil and plants work, but the level and frequency of fertilizer application is often based on experiments and field trials where yield and possibly some quality aspects are the main criteria for a relevant method. At first it might sound rational to base a fertilization theory on yield results, rather than on the plants need. After all it is human needs or aims we want to satisfy. But that reasoning is flawed.

Just because the theory of demand-driven fertilization is based on the needs of the plant, it doesn't entail that the aim of the theory is to satisfy the plants. Instead it means that, based on correct understanding of plants, it is possible to control them with greater precision in order to satisfy human needs. The problem with basing a fertilization strategy on desired yield results is that it can explain how to reach a certain result, but not why the result was reached or that it is the best way to reach it. It is empirical. In Figure 2 this principle is illustrated; both the demand-driven strategy and conventional strategies achieve the same thing, i.e. maximum relative growth rate, still both categories have different aims. The demand-driven strategy aims for concentrations close to that of optimum ($C_{n,\ opt}$), while the conventional strategies aims for concentrations within the sufficiency range without discernment. According to Figure 2 both strategies will achieve the same yield result, but due to mechanistic insight the demand-driven strategy will enable a more efficient management of resources, i.e. higher nutrient use efficiency and a lower risk for leaching losses.

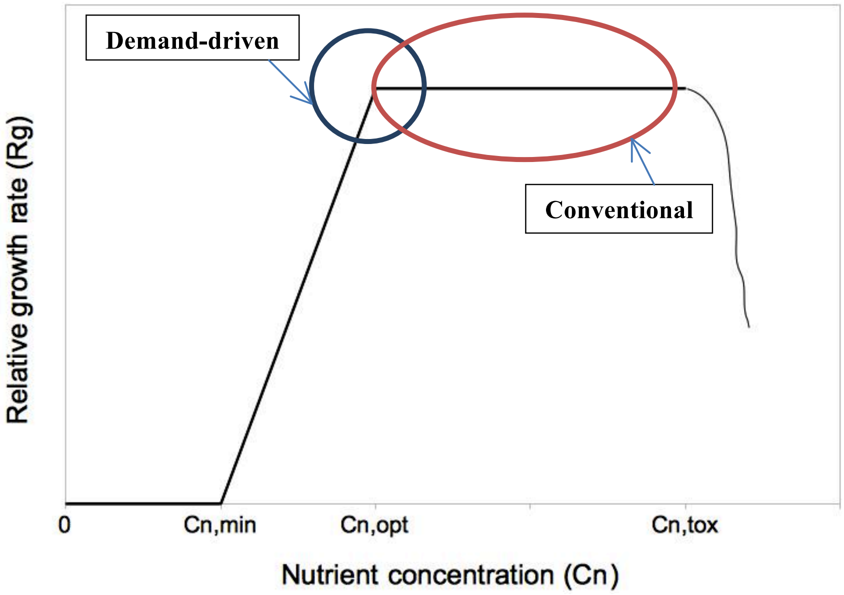

Figure 2. Relative growth rate (R_g) as the plants response to internal concentration of an essential nutrient. $C_{n,\ min}$ denotes the required minimum concentration of a nutrient necessary to trigger growth. $C_{n,\ opt}$ is an abbreviation for optimal concentration and denotes the concentration that if decreased it will trigger lowered (R_g) but if increased it can't trigger a higher (R_g). $C_{n,\ tox}$ is an abbreviation for toxic concentration and denotes at what point the concentration of a nutrient becomes toxic and the growth rate starts to decrease. The interval between $C_{n,\ min}$ - $C_{n,\ opt}$ is the response range, and the interval between $C_{n,\ opt}$ - $C_{n,\ tox}$ is the sufficiency range. (Knecht and Göransson 2004)

Secondly, the demand-driven method is based on a simple mechanistic mathematical model, describing a casual relationship between *relative uptake rate* and *relative growth rate*, which in turn can be controlled by the relative addition rate (Hellgren and Ingestad 1996). This simplicity and causality are traits that make the demand-driven strategy more trustworthy.

Thirdly, the research behind the demand-driven method is based on a methodology, in which physiological steady-state is upheld through maintaining stable internal nutrient concentrations by assuring a stable relative uptake rate, resulting in a stable relative growth rate. The relationship is formal, and statistical analysis cannot improve the estimation of uptake (R_U) [relative uptake rate] or growth (R_G) [relative growth rate] at a given and constant R_A [relative addition rate]. Such an analysis can only reveal technical inadequacies in the methods used to control R_U and R_G or to evaluate the results correctly (Ingestad and Ågren 1992). Thus, when no external variable limits growth, optimal internal nutrient concentration in the plant (according to Figure 2), corresponds to the maximal growth potential of the plant (Ingestad 1997, Hellgren and Ingestad 1992, Ingestad and Ågren 1995). Thus physiological steady-state enables a correct methodology and without it "empirical results that are not mathematically verified for acclimatized plants grown at steady-state cannot be used to formulate broad, general theories" (Ingestad and Ågren 1992).

Some objections have been raised against steady-state at maximum relative growth rate. First it may be objected that plants don't grow under steady-state conditions naturally and therefore results obtained from research with the steady-state methodology are not relevant. But this objection is according to Ingestad and Ågren (1995) flawed for two reasons:
(1) "although steady-state should be seen as an idealization, just as an ideal gas is a very useful approximation of many real gases, the steady-state condition yields accurate, reproducible and generalizing experimental results that cannot be achieved with experiments where steady-state is not maintained".
(2) "in many cases, the deviations from a true steady-state are small and results obtained and expressed as plant parameters under steady-state conditions are applicable. When conditions deviate more markedly from steady-state, we should still expect the concepts derived under steady-state to apply but that the parameterization could be different and that additional concepts to describe the deviation from steady-state might be necessary (compare again the ideal gas with real gases)".

Another objection that has been raised is that if plants are forced to grow at maximum relative growth rate in a steady-state condition, it will lead only to maximum growth, and inhibit the sexual phase and blooming, and it will only work in the exponential phase of the growth. This objection has some points, but only on a theoretical level. While it is true that if a plant is forced to absolute maximum growth, then all carbon and energy resources will be set to accommodate that, which in turn will lead to lowered quality and eventually inhibition of the sexual phase, at least in some cases. However, that is not the case in the reality outside meticulous laboratory experimenting. Furthermore, as is the case with the experiment of this paper, in reality the relative growth rate is slightly under maximum and follows a S-shaped curve. In such a case the nitrogen functions as the growth limiting nutrient. This does, however, not mean that the plants suffer from nitrogen deficiency. There won't be any nitrogen deficiency symptoms when the uptake of nitrogen and other nutrients harmonize with the growth, which it does. Instead the growth will be close to maximum, and the slight limit in growth will create a balance between income and outlay in the plant. Excess sugars from the photosynthesis can be utilized for blooming, defense chemicals, energy storage and feed for mycorrhiza and beneficial microorganisms (Ericsson 2007). Actually, it is possible to manipulate the plant into a whole range of things, by changing the relative growth rate into a new steady-state, according to the production aim; a good example is how the root-shoot ratio can be controlled according to preference (Rytter *et al.* 2003). Simply put the concept of steady-state and maximum growth is very accurate and useful for real life plant production.

A similar objection is that fertilization for maximum growth rate in steady-state only applies to the vegetative phase. In a rigid sense this is true, as the plants nutrient needs change between the vegetative and sexual phase. That change is mainly in the ratios in-between the nutrients, and it is a small change, and it primarily concerns the need for K. When the Ingestad team performed experiments on tomatoes, the K need increased to 80 per cent of the N need in the sexual phase (T. Ericsson, Swedish University of Agricultural Sciences, personal communication). This need for change in nutrient ratios are accounted for by the Ingestad theory, which can be seen in Table 1 in that some of the nutrient requirements are stated as intervals, and in particular the need for K However, in steady-state conditions that change is often less extreme than the full span of these intervals and thus only small adjustments in the fertilization regime are needed. Furthermore, the change in the plants needs between the two phases has no tangible effect in reality as the growth rate already is slightly lowered on purpose.

Emphasis needs to be put on two things in order to correctly portray the usefulness of the theoretical model of Ingestad. Firstly, the weakness of the theory is its focus on the vegetative phase of the plants. Plants often have different needs between the vegetative and sexual phase. This is particularly important if the quality of harvested plant part is dependent on other factors than the very need of the plant. Potatoes for example require higher K input than what actually is required by the plant in order to prevent brown spots, which in turn is essential for the producer to make the crop sellable. Furthermore, the nutrient supply curve must be limited in order to prevent the absolute theoretical peak growth rate. This is necessary in order to allow the crop to enter the sexual phase, and also to prevent lowered quality of harvest. This is usually done by the composition of the fertilizer where N serves as the limiting factor according to the principle of Liebig's law, thus creating a beneficent deficiency which keeps the growth rate close to maximum without ever reaching it. To establish the plant nutrient need during the sexual phase would be the next step in improving the Ingestad model. Secondly, even though focus lies on the vegetative phase and absolute correct precision is lacking during the sexual phase, when put to practice in real production the precision is accurate enough to ensure expected high yield and quality for most crops. For crops with special needs due to quality or other aspects, a simple adjustment is enough, such as extra S for rape seed, or extra K for fruit and root vegetables etc.

From a fertilization perspective, the nutrient use efficiency is the most important factor in order to counteract leaching, and in contrast to above objections, the three above listed theoretical merits of demand-driven fertilization, can be utilized to amend nutrient leaching with higher precision than what the other strategies can.

In contrast the empiricist approach in the other strategies is a problem when working toward optimum nutrition and minimized leaching. The study of fertilizer management and nutrient leaching is predominantly based on field studies and empiricism. Certainly this is true for open land production. Systems with fertigation and concentration-driven fertilization have a high degree of precision due to the mechanistic understanding of the relation between plant physiology and fertilization parameters. However, the research on those systems is often empirical studies of the effect of external concentration. Empiricism has weaknesses compared to correct mechanistic understanding, as was seen in Figure 2. This could be further illustrated by the typical experiment in which it is compared how two different external concentrations caused by two different fertilization strategies, affect growth, and drawing conclusion on nutrient demand from the nutrient concentrations in the plants. The problem with this approach is that when the plants are analyzed, their internal nutrient concentration most likely reflects that of their soil solution. It does not necessarily represent the nutrient need of the plants. Ingestad argues that:" a pseudo-science has in an empirical 'trial-and-error' research been based upon statistical evaluation of data that are of low quality. This is a problem of major significance that needs open discussion and public attention" (1997). Instead he thinks it should be concluded that "the commonly used driving variable for uptake, external concentration, should be abandoned since its form (lack of time dimension) makes it incompatible with the uptake rate" (Ingestad 1997). I understand his points to mean that statistical evaluation, no matter how strong is of no real worth if the data is of low quality and doesn't reflect an actual mechanism or behavior in the plant. It can create an illusion of science since the data reflects results in harvest that seems clear, when instead focus should be on how the plants actually functions. I think his argument is profound since there always is a risk for unscientific conclusions when based mainly on empiricism, and research of plant production often is dominated by empirical field trials.

However, empirical trials are presumably necessary for practical reasons, and will remain so since things need to be tested out without the burden to first unravel exactly how complex systems work. Many things in nature can't be expected to be discovered within the foreseeable future, either for the lack of resources or due to the complexity in nature. Still, it would seem that the predictive power and the documented and impressive results of the demand-driven method should create attention. But it has not. Why? Well, first of all, in many production systems solid fertilizers applied on a single or on few occasions have its place, especially in open land agriculture without irrigation. In such systems the Ingestad method is not relevant. Furthermore, the differences between agriculture, horticulture and silviculture probably make them resilient to learn from each other. Finally, a conservative attitude is present in the world of plant production and in the research thereof, something I have clearly witnessed as a student of the agricultural program. Whether Ingestads arguments are correct or not, it would presumably only come good from the open discussion and public attention requested by Ingestad. The correlation between empirical data for nutrient uptake and leaching is hard to establish, and therefore the more classical fertilization strategies have weaker potential to amend leaching.

A comparison of the fertilization strategies

All the main categories of strategies have pros and cons in the area of plant production. Strategies based on inorganic fertilizers with one or few applications are the most common way to fertilize in agriculture. It is simple, and it works in open land agriculture regardless of geography, soil type or climate. The downside of it is the risk for applying to much fertilizer, and the sensitivity for leaching as a result of heavy rains. Strategies based on organic fertilizer is also very common throughout the world, either as a complement to inorganic fertilization, or as in the poorer part of the world where it often is the only accessible way to fertilize, and of course as fertilization in outspoken commercial organic production. The biggest benefit is that it uses the manure, which is desirable and most convenient to recirculate rather than to put in deposits, as deposits often leads to environmental problems through leaching. Furthermore, it increases the organic matter in the soil which in turn often maintains the long time fertility of the land. The downside is the high risk for N leaching. In modern high yielding production, organic fertilizer should not be applied in high quantities but be managed in a way in order to recycle it without creating environmental problems. Instead it should be complemented with another fertilization strategy. Strategies based on fertigation have many benefits from a production perspective. It increases nutrient use efficiency, it lowers the risk for leaching, it controls how the plant grows and it has high precision through its application systems. It would probably be the best option for any greenhouse production. The downside of it is that is not a feasible option in most of the non-arid world where there is no need for irrigation or where such a heavy investment simply isn't economically justifiable. In classical fertigation where the fertilizers are applied as a nutrient flux in amounts over time has the benefit of being applicable in any irrigation system regardless of precision. The downside is that is has relatively low precision. Fertigation performed as concentration-driven strategy can with advantage be used in closed circulation systems in greenhouse production. However, I see no real benefit with it. It seems simple to only keep track of a concentration, but why complicate fertigation with such a counterintuitive and complex concept as fertilization through concentration; why not just give the plant what it needs in amounts of each nutrient when it needs it. Demand-driven fertilization is just that; to give the plant what it needs, when it needs it and in correct doses. Therefore, fertigation in the form of a demand-driven strategy seems both simple, effective and with very low leaching risk.

Conclusions

The demand-driven strategy has the highest potential to minimize leaching, if the production system allows for it to be used. All fertigation based strategies hold high potential for lowering the leaching, but the methods could be improved by incorporating the theory of Ingestad in its implementation.

Further research should be expected to be fruitful as this and other studies implies great possibilities to utilize the theory of Ingestad, but those implications for decreased leaching should be evaluated and further substantiated in more comprehensive studies where the whole life-cycle of the plant can be studied and preferably in a study of larger scale. Fertilization methods need to be developed in order to implement the theory in agriculture, greenhouse production and gardening etc, and as a basis to improve other strategies.

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Appendix

The model of Ingestad

Nutrient ratios

The research of Ingestad and coworkers led to the conclusion that all plants have the same basic physiology and consequently need the fourteen different essential nutrients in more or less fixed proportions. The total need of nutrients, however, differs between species. Due to morphology, plants have different growth capacity, and as growth capacity increases so does the nutrient demand. (Ericsson 2007)

In climate chambers, the research group made experiments, where the plants were given free access of essential nutrients, in very frequent and small doses (Ericsson 2006). Species included in the research were birch, basket willow, poplar, alder, eucalyptus, Norway spruce, Scots pine, cucumber, tomato, blueberry, lingonberry, duckweed and the four types of grain. The research group discovered that the nutrient ratios were very similar for all plants involved when they grew at maximum rate, with small variations as displayed in Table 1. These ratios are close to but not necessarily the exact theoretical optimum for every species. These ratios were further supported for N, P, K, Ca and Mg by a literature study performed by Knecht and Göransson (2004) with the aim to examine nutrient ratios in terrestrial ecosystems. The proportions calculated out of the literature were found to correspond closely to the proportions determined in laboratory and field experiments. Distinctive patterns were observed, that corresponds to both theoretical predictions as well as to laboratory experiments, despite the variations in the ratios between the nutrients that occur in nature (Knecht and Göransson 2004). Thus Ingestad recommended that the nutrient ratios in Table 1 should be aimed for in virtually any fertilizing program in real world production, with only small consideration for alterations due to deviant crops or circumstances (Ericsson 2006, Knecht and Göransson 2004). Due to correct ratios between the nutrients, this concept would in most cases presumably lead to increased nutrient efficiency and consequently to lowered nutrient leaching or nutrient storage in soil. According to Ingestad these ratios answers the question what the plants need.

The mechanistic conceptual model of Ingestad and coworkers

Ingestads research group created a theory in accordance with the research results of the team. Their theoretical model describes the processes of nutrient flux in the soil and the rhizosphere, nutrient uptake and nutrient utilization.

The theory is outlined below in a simplified manner. The first section describes the biology of the plant, and the second section describes the soil properties governing nutrient availability. The outline is based on the research of Ingestad (1982, 1988) together with Ågren (1992).

Theory of plant physiology

1. Growth is the basis for nutrient consumption. Growth is defined as *relative growth rate* (R_G), i.e. increase in mass per total plant biomass and unit of time.
2. Relative growth rate is a linear function of the internal concentration of each essential nutrient, from a minimum effective concentration up to an optimal one, where the nutrient productivity is the proportionality factor.
3. In order to keep up the internal nutrient concentrations, the required *relative uptake rate* (R_U) will be the equal of relative growth rate.
4. To satisfy relative uptake rate for each nutrient as the plant is growing according to its own non-restrained growth pattern, the addition rate must increase in an exponential manner with a *relative addition rate* (R_A) which is equal to the R_G.
5. Relative addition rate can then be used as a driving variable for uptake and growth, up to and including a relative addition rate value which is equal to *the maximum relative growth rate* (R_{Gmax}).

Soil scientific theory

1. The soil has a natural *nutrient delivery capacity* (N_{DC}) for N and P which is controlled mainly by the mineralization rate.
2. The nutrient delivery capacity is quantified as *nutrient flux density* (D_N), i.e. the amount of each nutrient available per unit of soil and unit of time.
3. Correct relative addition rate to the soil can then be established from the nutrient flux density of the soil and the relative uptake rate of the crop.

The uptake capacity increases during growth season according to S-shaped curves governed by genetically determined plant development and climatic conditions. Consequently, the supply of the nutrients should follow an accumulated S-curve, i.e. smaller doses in the beginning and the end of the season, and the highest dose when growth rate is at its peak, and in a frequency high enough, so that the uptake capacity is satisfied continually over the season. Thus, there are three aspects of the soil-plant system that must be properly understood in order to implement this fertilization strategy:

1. The physiologically determined nutritional need, i.e. the recommended ratios and the total nutrient demand.
2. The properties of the soil that affects its nutrient flux density.

3. Climate and geographic conditions.

Consequently, a fertilization program can be made, in which the nutrient flux density is modified to match the relative addition rate curve, and thus satisfy the nutrient uptake capacity over the vegetation period.

The mathematical model of Ingestad and coworkers

In accordance with the theory, Ingestad and Ågren created a fertilization model based on the concepts of nutrient flux density and nutrient productivity. The model is a synthesis of the plant specific genetically defined nutrient demand and the nutrient flux density of the soil. The model is also based on the universal similarity of the essential nutrients according to recommended ratios. The model is nothing else than a mathematically precise quantifiable version of the theory outlined above. (Ingestad 1988)

Effect of demand-driven fertilization on yield and leaching in experiments

The theory of Ingestad and coworkers has shown great power to predict growth, nutrient uptake and fertilizer consumption with accuracy and precision, and their model for fertilizer application has shown an ability to predict growth, biomass and internal nutrient concentrations very accurately (Hellgren and Ingestad 1996, Ingestad and Ågren 1992, Ingestad and Ågren 1995). Several examples have been reported where the demand-driven strategy of Ingestad has shown to have higher nutrient use efficiency, similar or higher yield levels and less leaching than conventional fertilization strategies (Ingestad 1982, Kätterer and Andrén 1996, Kätterer *et al.* 1997, Rytter et al. 2003)