Optimization of plant mineral nutrition revisited: the roles of plant requirements, nutrient interactions, and soil properties in fertilization management

Anita Osvalde*

Laboratory of Plant Mineral Nutrition, Institute of Biology, University of Latvia, Miera 3, Salaspils LV-2169, Latvia

*Corresponding author, E-mail: augi@email.lubi.edu.lv

Abstract

The aim of the present review is to provide a summary of the research on plant mineral nutrition diagnostics and optimization carried out during 1950 to 1990 in the Laboratory of Plant Mineral Nutrition, Institute of Biology, University of Latvia, under the supervision of professor G. Rinkis. The results of this large-scale and long-term investigation have been published as numerous monographs, dissertation theses and scientific papers. Based on the obtained results, a complex method for optimization of plant mineral nutrition was developed. The main achievements and principles of these studies are widely used today in different research directions of plant mineral nutrition in Latvia: plant adaptive responses to different environmental stresses (heavy metal pollution, salinity, and nutrient imbalances), growth optimization of new crop cultures etc. Only a limited part of this broad scientifically and practically valuable work is included in the present review.

Key words: agriculture; fertilization management; optimization of nutrient supply; plant mineral nutrition.

Relevance of the problem today

Although plant mineral nutrition and optimization of mineral supply has been the subject of numerous studies for decades since the 19th century, today there is still controversy about the methods for diagnostics and fertilizer management designed to obtain optimal plant productivity and sustainability in agriculture. Presently, poor soil fertility, low levels of available mineral nutrients in soil, inapropriate nutrient management strategies, along with the lack of plant genotypes having high tolerance to nutrient deficiencies or toxicities are major constraints contributing to food insecurity, malnutrition and eco-system degradation.

In general, plant nutrition research can provide highly valuable information that can be used to eliminate the above-mentioned constraints, and thus, can lead to sustained food security and well-being of human society without harming the environment. The fact that at least 60% of cultivated soils have plant growth-limiting problems associated with mineral-nutrient deficiencies and toxicities, and about 50% of the world population suffers from micronutrient deficiencies, makes plant nutrition research a major promising area for meeting the global demand for sufficient food production with enhanced nutritional value in this millennium (Loneragan 1977; Cakmak 2002; White, Brown 2010).

A projected high increase in global fertilizer consumption (FAO 2000), reaching up to 200 or even 300 millions of tons in 2020, raises concerns due to low nutrient use efficiency and inapropriate soil management. Analysis of element and nutrient balances or budgets at different levels (farm-gate, field balance, and soil system balance) has become widely adopted as a tool in the transition towards a more sustainable agriculture. However, there are broad differences in development and application of this direction even within the European Union countries (Öborn et al. 2003). Although nutrient budgeting has been practicised for more than a century, there still are a lack of well-documented and widely accepted procedures and guidelines for implementation of the method and for analysis of uncertainties (Oenema et al. 2003).

The commonly used methods for estimation of soil fertility and approaches in fertilizer research and management may be insufficient to achieve the required increase of efficiency because they are either too general or too empirical. Evaluation of intensive grain production systems in the United States and Asia revealed the following main challenges: farm yields presently are only about 40 to 65% of the attainable yield potential, and nutrient management mostly relies on approaches that do not account for the dynamic nature of crop response to the environment. Therefore, complex approaches based on interdisciplinary research (soil chemistry, crop physiology, plant nutrition, molecular biology, and information technology) are necessary to develop nutrient management systems that optimize profit, preserve soil quality, and protect natural resources in a way consistently producing high yields (Dobermann, Cassman 2002).

Reaching the goals of sustainable nutrient management in agriculture at a large scale ultimately depends on how nutrients are practically managed at the farm level. Therefore, nutrient management as an activity must focus on the synchronization and synlocalization of supply and demand of plant nutrient sources both in space and time (Oenema, Pietrzak 2002). This requires a system for optimization of availability of soil nutrients. Today, most element balance systems at the farm level contribute little to the recognition and quantification of internal element flows, and, in fact, often neglect them completely (e.g. Watson, Atkinson 1999).

Integrated nutrient management can be defined as reasonable manipulation of nutrient stocks (inputs/outputs) and flows in order to achieve satisfactory and sustainable levels of agricultural production (Deugd at al. 1998). Integrated nutrient management can only be carried out by farmers who are experts at managing their complex soils, using scientific results in real-world practice.

Today, in Latvia nutrient management (fertilization) plan is an obligatory element for integrated farming, and for agricultural crop production in nitrate-sensitive areas (European Comission 1991). Although these plans embrace nutrient balance (N, P, and K) for target productivity, manure management and crop rotation effect etc., there are many uncertainties and general assumptions. Therefore the following question arises: are element balances (accounting systems) the best tool for optimizing agricultural nutrient use efficiency and decreasing negative environmental impact of nutrient loss? Evidently, a task and challenge for researchers is to develop novel strategies for more accurate nutrient management systems including clear targets, scientifically sound principles and efficient tools for the specific agroecosystems and site conditions.

Studies on plant mineral nutrition diagnostics and optimization, carried out during 1950 – 1990 in the Laboratory of Plant Mineral Nutrition at the Institute of Biology, University of Latvia, under the supervision of professor G. Rinkis led to the development of a complex method for optimization of plant mineral nutrition, which was based on an approach completely different from nutrient budget systems. This method can be characterized as an accurate site-specific nutrient management strategy, mainly considering plant nutrient demands, nutrient interactions, soil and meteorological factors.

It should be stressed that the development of precision fertilization techniques for site-specific crop management is considered as one of the great challenges for plant nutritionists in the 21st century (von Wirén 2011). Therefore, revision of previous complex plant nutrition studies, which are scientifically up-to-date and practically valuable, can contribute to future advances in this scientific discipline.

Background and objectives

The basic principle of the research on plant nutrition carried out at the Institute of Biology was that all the main factors affecting plant growth and development are interrelated, equally important and essential. Moisture supply, temperature, light and soil properties affect both soil mineral availability and nutrient uptake, as well as accumulation within the plant. Therefore, optimization of one of these factors, e.g. mineral nutrition, without normalizing the other environmental conditions and agrotechnical measures, still might result in a limited plant growth and yield.

The studies on optimization of plant mineral nutrition were complex and included four main research objectives: (i) evaluation of specific requirements for macro and micronutrients (N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, Mo, B) of plants or a particular crop; (ii) studying the interactions among nutrients during their uptake by plants; (iii) understanding the effect of soil properties (composition) on nutrient accumulation in plants; and (iv) the development of a complex method for optimization of plant nutrient supply.

The main results of these studies are published in detail in numerous scientific publications and presented at international and local conferences (Rinkis 1972; Rinkis 1973; Rinkis, Nollendorfs 1977; Rinkis, Nollendorfs 1982; Riņķis, Ramane 1989; Riņķis et al. 1989; Riņķis et al. 1995).

Studies on plant requirements for macro- and micronutrients – optimal concentrations in inert growth medium

Studies on plant requirement for macro- and micronutrients were based on two main principles. Firstly, as all mineral nutrients are equally essential and their uptake is interrelated, the optimum concentration of a particular nutrient in soil should be estimated in accordance to the optimal concentration of other nutrients. Secondly, nutrient absorption capacity of the soil is another important factor affecting optimal soil concentrations. Since soil conditions vary significantly even in the same cultivation area, field experiments on plant nutrient requirement are practically pointless. Therefore, studies with various crop cultures need to be carried out in inert (no reactions with nutrients) substrate – quartz sand – at controlled optimal environmental conditions (moisture, temperature, light).

The selection of a quartz sand as a substrate was based on the following criteria: inertness, porosity, application without processing, and easiness of refinement, and similarity to soil. It was assumed that the uptake of nutrients by plants from a growth medium without absorption capacity occurs directly and depends considerably on the concentrations and nutrient ratios in the substrate (Rinkis 1972).

Table 1. Nutrient concentrations and ratios in plants and inert substrate (Rinkis 1972; Rinkis 1973)

Nutrient	Plant tissues		Substrate	
	Mean concentration (mg kg^{-1})	Ratio to P or Cu	Selected ratio	Approximately optimal concentration (mg L^{-1})
N	12 000	3.4	2.0	120
P	3 500	1.0	1.0	60
K	10 200	2.9	2.5	150
Ca	7 000	2.0	3.3	200
Mg	3 500	1.0	1.0	60
S	3 000	0.9	0.9	50
Fe	130	15.0	17.0	5
Cu	8	1.0	1.0	0.3
Zn	25	3.1	3.3	1
Mn	50	6.3	7.0	2
Co	0.4	0.05	0.10	0.03
Mo	0.7	0.03	0.07	0.02
B	5.4	0.7	0.7	0.2

Mean nutrient concentrations and their ratio in tissues of cereals, vegetables and perennial grasses were chosen as a basis for determining the approximate optimal concentrations of macro and micronutrients in the inert substrate. The nutrient level in substrate was calculated mostly based on these ratios and a set of optimal level of phosphorous, equal to 60 mg L^{-1} (Table 1).

For these calculations, the ratio of macronutrients to P concentration and ratios of micronutrient concentrations to Cu concentration were determined. These two elements were chosen due to the relatively stable concentration of these nutrients in a wide range of different plant tissues. As the estimated sum of the total concentration for macronutrients in plants reached 40 000 and for micronutrients – 200 mg kg^{-1}, the Cu level was calculated from concentration of P as 60 / 200 = 0.3 mg L^{-1} (Rinkis 1972; Rinkis 1973).

Large-scale vegetation experiments with lettuce, barley, buckwheat, oat, lupine and broad beans were carried out to test and fine-tune the putative optimal nutrient concentrations in quartz sand substrate. Based on these results optimal concentrations of particular nutrients were calculated for different plant crop groups grown in inert substrate (Table 2).

It should be noted that given nutrient concentrations are referable to nutrient free, weakly acidic quartz sand without any particles of clay and mica. In addition, very fine $CaCO_3$ was used as a source of Ca. In other conditions, concentrations of Ca and micronutrients, especially Fe, should be increased two to three-fold (Rinkis, Nollendorfs 1982).

Table 2. Optimal concentrations of nutrients in inert substrate, mg L^{-1} (Rinkis, Nollendorfs, 1982)

Nutrient	Cereals	Legumes	Vegetables
N	100 – 120	60 – 80	120 – 150
P	40 – 50	40 – 60	60
K	120– 150	150	150 – 200
Ca	200	200 – 250	300
Mg	50	60	60
S	50	70	70
Fe	5 – 10	5 – 10	5 – 10
Cu	0.3	0.3 – 0.4	0.4
Zn	0.5 – 1.0	1.0	1.0
Mn	1.0 – 2.0	2.0 – 3.0	2.0 – 3.0
Co	0.03	0.04	0.04
Mo	0.01 – 0.02	0.02 – 0.03	0.02 – 0.03
B	0.1 – 0.2	0.2 – 0.3	0.3 – 0.4

Interactions among mineral nutrients in plant nutrition

Agricultural soils all over the world are very heterogeneous and crop production is often limited by low phytoavailability of essential mineral nutrients and/or the presence of excessive concentrations of nutrients in the soil solution. Interactions between nutrients, both in the growth medium of the plant as well as within plant tissues, can lead to deficiency or toxicity of particular minerals, as a result decreasing plant growth and crop yield. Therefore, a second direction of research was devoted to studies on the effects of nutrient disbalance in substrate on nutritional status of plants. Optimization of all nutrients except the studied one and provision of optimal growth conditions (moisture, temperature, light) during all experiments were used as the main principles.

In the first set of experiments, changes of nutrient concentration balance in plants in response to small deviations of concentration (30 – 100%) of one nutrient from optimum in substrate were determined. The obtained results proved firmly that disbalance of any nutrient affects life processes of plants and is closely related to the uptake of other nutrients. An increase in concentration of a nutrient up to the optimal level promoted absorption of other nutrients (synergism), while an excess level inhibited the accumulation of nutrients (antagonism). Consequently, the highest biomass production and nutrient accumulation was associated with optimal supply of both macro and micronutrients (Rinkis 1972).

In the second stage of experiments, the impact of a drastic (three to 250-fold) increases of concentration of one nutrient and decrease from optimum on accumulation of other nutrients in plants was evaluated. The results revealed three peaks of nutrient concentrations in plants: (i) at optimal level; (ii) at drastic deficiency and (iii) at high

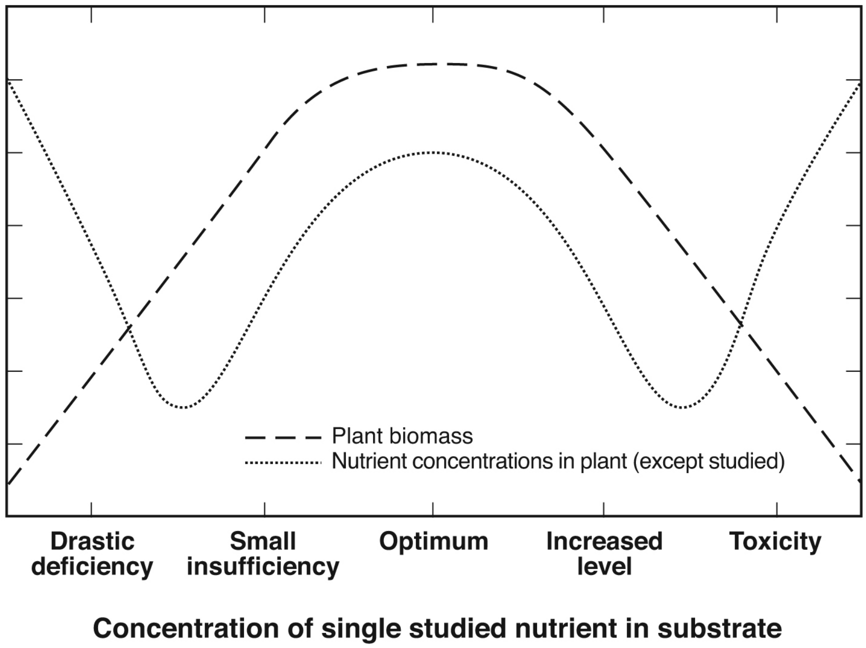

Fig. 1. Effect of different levels of particular nutrient supply (from deficiency to toxicity) in substrate on biomass production and nutrient accumulation in plants (Rinkis, Nollendorfs 1982).

toxicity. Plant responses to different levels of supply of one nutrient (from deficiency to toxicity) by biomass production and mineral element accumulation are schematically shown in Fig. 1. It was concluded that manifestation of synergistic and antagonistic interactions are not permanent and can be specific for any individual pair of nutrients. To a great extent, this phenomenon depends on nutrient concentration deviations from optimum in substrate for a particular crop culture (Rinkis, Nollendorfs 1982).

Studies were also conducted on means to eliminate the negative effect of toxic contents of nutrients in substrate on plant biomass production. Although plants require a sufficient, but not excessive, supply of nutrients for optimal productivity, agricultural soils frequently contain inadequately high or even toxic levels of particular nutrients. Previous studies on interrelated impact of nutrients, their antagonism or synergism, proved firmly the ability of one particular nutrient to inhibit or to stimulate the uptake of other nutrients. Therefore, it was hypothesized that by purposeful changes in biogenous nutrient supply, the level of toxic nutrient accumulation and their impact on plants could be controlled significantly.

The experimental results suggested that the negative effect of excessive P, Cu, Zn and Mn could be considerably

Table 3. Concentrations of nutrients (mg L^{-1}) suitable for elimination of P, Cu, Zn, and Mn toxicity (Rinkis et al. 1989; Rinkis, Ramane 1989). * 20% of indicated amounts should be used in the conditions of simultaneous toxicity of various nutrients

Toxic nutrient	Excess concentrations		Counteracting nutrients								
	Mineral soils	Peat soils	N	P	K	Ca	Mg	Fe	Zn	Mo	B
P	400 – 500	300 – 400	10	-	40	1000	130	80	2	–	0.1
	500 – 600	400 – 500	15	-	50	1500	200	120	3	–	0.15
	> 600	>500	20	-	60	2000	250	150	4	–	0.2
Cu*	20 – 30	30 – 40	5	10	20	400	50	60	1	0.03	–
	30 – 40	40 – 60	10	20	30	500	60	80	2	0.04	–
	>40	>60	15	30	40	600	70	100	3	0.05	–
Zn*	40 – 60	20 – 30	5	20	–	300	40	60	–	–	–
	60 – 80	30 – 50	10	30	–	400	50	70	–	–	–
	>80	>50	15	40	–	500	60	80	–	–	–
Mn*	150 – 250	50 – 75	5	20	–	800	100	100	–	–	0.1
	250 – 350	75 – 125	10	30	–	1200	150	150	–	–	0.15
	>350	>125	15	40	–	1500	200	200	–	–	0.2

Table 4. The efficiency of regulated mineral nutrient supply as a measure for elimination of P, Cu, Zn and Mn toxicity in experiments with barley (Rinkis et al. 1989; Rinkis, Ramane 1989)

Treatment	Barley grain yield (%)	
	In respect to optimal nutrient supply regime	In respect to corrected nutrient supply regime
Control (all nutrients in optimal concentrations)	100	–
P toxicity (P_{550})	46	116
Cu toxicity (Cu_{20})	25	108
Zn toxicity (Zn_{60})	56	103
Mn toxicity (Mn_{80})	42	84

diminished by increasing the levels of Ca, Mg and Fe, as well as N, P, K, Zn, Co, Mo and B in substrate (Riņķis et al. 1989; Riņķis, Ramane 1989). A multitude of experiments were focused on elucidation of accurate concentrations of nutrients necessary to correct these toxicities (Table 3). The results of these studies convincingly demonstrated the effectiveness of corrected mineral nutrition in preventing the negative effect of excess P, Zn, Cu, and Mn. For example: barley grain yield under both toxic and corrected nutrient regimes are shown in Table 4. This investigation formed the basis for further studies on plant protection mechanisms under conditions of stress caused by imbalance of nutrients and the toxicity of heavy metals in the growth environment (Osvalde, Riņķis, 1998; Osvalde 2001; Osvalde, Paegle 2005).

Effect of soil properties on nutrient accumulation in plants

A set of model experiments was conducted on different crop cultures to evaluate and quantify the effect of soil properties on nutrient uptake. Quartz sand fractions of different particle size, various amounts of kaolinite, peat, humic acids, iron and aluminium oxides, and calcium carbonate were used as substrate models. It was found that soil texture, pH level, and organic matter, carbonate, Fe and Al oxide content are important parameters that significantly affect availability of nutrients (Rinkis, Nollendorfs 1977; Rinkis, Nollendorfs 1982). Particular changes in the physical and chemical soil characteristics resulted in a significant decrease in nutrient accumulation by plants. For example, increased organic matter content in the substrate clearly reduced nutrient availability to plants (Fig. 2). Molybdenum was the only exception, showing increasing accumulation in plant tissuess with the increase of the substrate pH.

To compensate for the negative effect of soil physical and chemical properties on plant nutrient availability and, consequently, to optimize mineral nutrition, additional excess amounts of particular nutrients should be supplied in the growing medium. The particular doses needed were identified and tested experimentally (Table 5).

Complex method for optimization of mineral nutrition

Based on the obtained results, a complex method for balanced mineral nutrition of plants was developed (Riņķis,

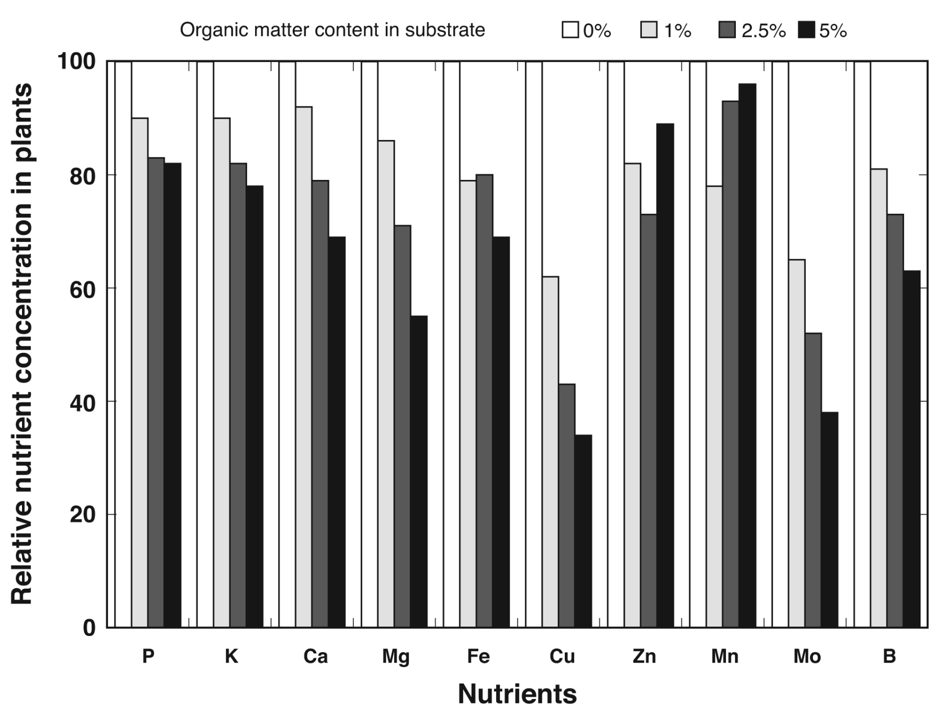

Fig. 2. Effect of organic matter content in substrate on mean nutrient concentrations in plant tissues (Rinkis, Nollendorfs 1982).

Table 5. Recommended amounts of nutrients (mg L^{-1}) for compensation of the effect of soil properties (Riņķis, Ramane 1989). The data indicate the necessary amounts based on 1% increase of the particular parameter. For a particular soil, amounts in the table should be multiplied by the exact content (in %) of each parameter – fine sand, clay etc.

Nutrient	Fine sand	Clay	Peat	Organic matter	Humic acids	Fe and Al oxides	Carbonates	Each 0.1 of pH above 5.0
N	0.3	0.6	0	0	0	0	2.5	0
P	0.9	1.8	0.7	5.0	10.0	20.0	12.0	2.4
K	0.3	0.6	1.0	5.0	10.0	0	6.0	1.5
Ca	6.0	12.0	30.0	200.0	400.0	60.0	0	0
Mg	0.8	1.5	4.0	25.0	50.0	12.0	20.0	1.0
Fe	0.6	1.0	1.0	10.0	20.0	0	10.0	2.0
Cu	0.009	0.018	0.05	0.2	0.4	0.18	0.06	0.018
Zn	0.03	0.05	0.03	0.15	0.3	0.35	0.5	0.1
Mn	0.1	0.1	0.02	0.4	0.8	4.0	4.0	1.0
Co	0.002	0.004	0.005	0.024	0.04	0.03	0.04	0.004
Mo	0.0003	0.0006	0.0016	0.008	0.016	0.029	–0.002	–0.0006
B	0.003	0.006	0.008	0.04	0.08	0.1	0.02	0.004

Ramane 1989; Riņķis et al. 1995). It should be noted that optimization measures in accordance with this method should be performed in two different (in time and targets) stages. The first stage involves providing a stable and balanced mineral nutrition regime for the plants in the particular soil, and the second is necessary to maintain the conditions necessary for optimal plant mineral nutrition. The essence of the method is summarized in Fig. 3.

The practical use of this method is rather complicated and requires additional measures of preliminary soil management to increase productivity, in addition to reliable analytical support (both soil and plant testing) and significant agrochemical expertise. In spite of the complexity, high efficiency in terms of crop yield (Table 6) and quality has been achieved in numerous field experiments carried out in different regions of Latvia (Riņķis et al. 1989). An accurate diagnosis, corrections of essential nutrient (N, P, K, Ca, Mg, S, Fe, Mn, Zn, Cu, Mo, B) deficiencies and toxicities for the particular crop in the particular soil conditions, as well as additional fertilization in response to climatic conditions to cover leaching losses and to maintain plant requirements during the whole

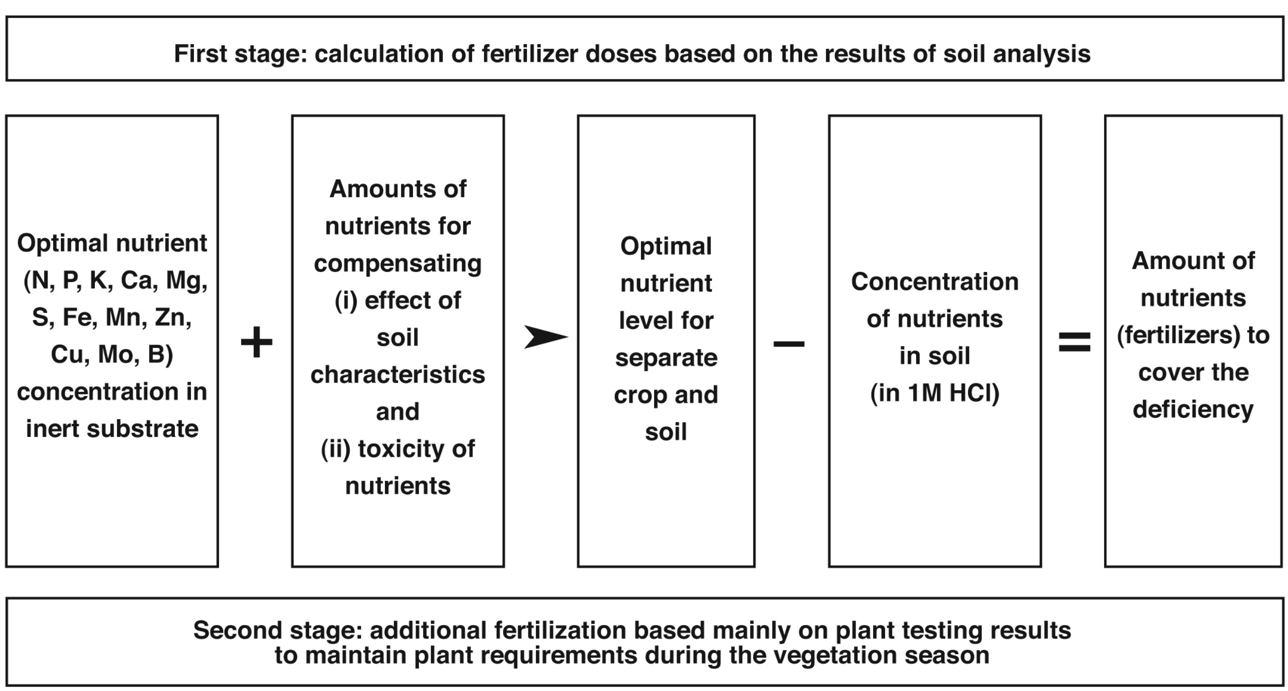

Fig. 3. The scheme of complex method for optimization of plant mineral nutrition (Riņķis et al. 1989; Riņķis, Ramane 1989).

Table 6. The effect of fertilizer supply in accordance with the complex method for optimization of plant mineral nutrition on average yields of different crop cultures (Riņķis et al. 1989)

Crop	Average crop yield (t ha^{-1}) at different fertilization practices		
	According to conventional recommendations (N, P, K)	According to the first stage of complex optimization method (fertilizer doses based on soil analysis)	According to the first and the second stages of complex optimization method (basic and additional fertilization)
Barley, grain	3.6	4.9	6.0
Oat, grain	3.0	6.0	7.3
Potatoes	18.0	45.0	71.2
Maize, green mass	4.5	9.5	12.5
Red clover, hay	5.0	6.4	11.0
Timothy, hay	5.5	9.0	10.6
Red beet	25.0	68.0	85.0
Carrot	20.0	48.0	93.4
Cabbage	60.0	107.0	161.5

vegetation season are key factors in achieving at least a two-fold increase in productivity. However, it should be noted that at present the average potato yield in conditions of Latvia is only 16 to 18 t ha^{-1}, the average grain yield (barley, oat) did not exceed 3 t ha^{-1} and there is little evidence that the average yields have increased significantly in the past 20 years (www.csb.gov.lv).

It should be point out that the complex method for optimization of plant mineral nutrition developed by Rinkis and colleagues is extremely relevant also in the present economical and environmental situation, because it meets all of the principles of integrated agriculture and environmentally-friendly (wise) use of fertilizers and allows to reach high income from agricultural productivity. For example, average cereal yields in Denmark, Germany, UK, Switzerland, and Belgium range from 6.2 to 7.7 t ha^{-1} (World Bank 2003). Using the described optimization method for commercial and environmental reasons plant fertilization is a site-specific decision and should be based on accurate analytical basis, should account for annual loss of nutrients, and rely on improved agronomic practices. Therefore, a full explanation of this method needs a special review.

Although complete optimization of nutrient supply, in the scientific sense, is an unreachable goal, its approximation is worth great effort. Currently, the major challenges for plant scientists and practicioners are to enhance crop yields in more recourse-efficient cropping systems and to stabilize plant development and yield formation under less predictable growth conditions due to global climate change (Reynolds et al. 2009).

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