# Crop yields and NPK use efficiency of a long-term experiment on a former sea bottom in the Netherlands

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The publishing of this report is under responsibility of the chair-group of Plant Production Systems.

Information on the publication is available via the office of Plant Production Systems
(e-mail: office.pp@wur.nl).

The photographs on the cover of this book were provided by Ing. Bert Rijk (Plant Production Systems) and Ing. Joop Overvest (former manager of Ir. A.P. Minderhoudhoeve). The composition of the cover was made by Andrew van Ingen. The statues on the right-hand photograph were designed by Wim Korvinus; they symbolize the waves of the original Zuyderzee, furrows in plough-land, and cereals rustling in the wind.

DOI: 10.18174/409554     ISBN: 978-94-6343-130-9

# Preface

In 1968, Wageningen University started an experimental farm in Oostelijk Flevoland, located between Lelystad and Swifterbant. The farm was named the Ir. A.P. Minderhoudhoeve. Several (sub-) departments of the university carried out field experiments at the farm.

In 1974, dr. ir. J.H.G. Slangen of the sub-department of Soil Fertility and Fertilizer Use, chaired by Prof. dr. ir. A. van Diest, proposed a project to study the changes in soil fertility in a long-term experiment. The trial began in 1975 under the scientific responsibility of dr. Slangen. Ing. J.W. Menkveld was in charge of the work in the experimental field, and Ms. W. van Vark of the chemical analyses. The manager of the A.P. Minderhoudhoeve (Ing. J Overvest) took decisions on crop husbandry.

Unfortunately, dr. Slangen passed away suddenly in 1990. The scientific responsibility of the long-term experiment was transferred to dr. ir. B.H. Janssen, while Ing. Menkveld and Ms. van Vark remained on duty.

The long-term experiment ended in 2002, when the university closed the experimental farm. Before 1990, preliminary results had been presented by Slangen and Menkveld in annual internal reports of the department of Soil Fertility and Fertilizer Use. After 1990, some further information was published in a number of conference papers. This book is the final reporting on the long-term experiment. It was composed by dr. Bert Janssen, while Ms. Hanna Kool MSc took care of the final formatting. Both are affiliated with the chair-group of Plant Production Systems of Wageningen University, a group that was and still is involved in several studies in Flevoland.

This study deals not only with the yields obtained during the 28 experimental years, but also with availability, uptake, balance and optimum use efficiency of soil and fertilizer NPK. For the assessment of availability and balance among N, P and K, rather unconventional methods have been developed and applied by Dr. Janssen. These methods build on his long and deep experience with fieldwork in both developed and developing countries, as well his great ability to summarize principles in summary models and concepts. The models and concepts are of strong scientific *and* applied value, as proven by the numerous citations of his work and the many applications of, for instance, his QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model in different past and recent research and development projects. We therefore anticipate that the methods presented in this book may also assist agronomists and soil scientists and serve as a toolbox for the interpretation of research data of fertility of soils well beyond one of the youngest polders of the Netherlands.

Since his ‘official’ retirement in 2004, Bert Janssen has been a loyal researcher at the Plant Production Systems group. He has hardly missed an MSc colloquium, a PhD defence or a lunch discussion meeting. Often the first to raise his hand to ask a penetrating question, he has kept us on our toes about all matters to do with soil, nutrient management and agricultural production in general. Further, he always has time for students and staff alike when we have difficult questions to research or discuss and he has co-authored many papers with us. This is Bert’s last publication – at least until something controversy triggers him to respond! We are truly grateful for all his input over the past years and it has been our pleasure to host him.

Prof. dr. ir. Martin van Ittersum
Prof. dr. Ken Giller
Plant Production Systems

# Acknowledgements

The first steps to enter into the research reported on in this book were taken in 1974, and the last steps to finish the report were taken in 2017. Several people who had been involved in the project during the initial years could not witness the completion, some others who joined during the later stages had not yet been born at the beginning of the programme.

I gratefully remember my colleague dr. ir. J.H.G. (Huub) Slangen who proposed the project to study the changes in soil fertility in recently reclaimed marine clay soils in Flevoland. He followed these changes with great curiosity before he suddenly passed away halfway the long-term experiment.

Also prof. dr. ir. A. (Tom) van Diest, chair of the group of Soil Fertility and Fertilizer Use until his emeritus status in 1990, was much interested in the developments appearing in the long-term experiment.

Ing. J. (Joop) Overvest was the manager of the Ir. A.P. Minderhoudhoeve and he decided about field and crop husbandry activities by his co-workers. He recently took some of the pictures shown on the cover of this book.

From the beginning to the end, Ing. J.W. (Willem) Menkveld and his co-workers of the ‘tuin’ did the experiment related work in the field in Swifterbant. Willem also carefully carried out the administration and the computing of the results at the department. His documents and some internal reports he co-authored form the basis of the present report.

Ms W. (Winny) van Vark and her co-workers accurately analysed the crop samples in the period 1994-1999. Without these analytical data, the study of NPK use efficiency would not have been possible.

Previous versions of one or more chapters of this book were reviewed by the late prof. dr. ir. J.H.J. (Huub) Spiertz, by dr. ir. L.R. (Rob) Verdooren and dr. ir. A.G.T. (Tom) Schut, and lastly by prof. dr. ir. M.K. (Martin) van Ittersum and Ing. Bert Rijk. The quality and the scientific soundness of the text have improved considerably by their critical comments.

Finally, Hanna Kool MSc enthusiastically and conscientiously formatted the book.

I feel very much obliged to all of them. A special word of thanks goes to prof. dr. Ken Giller and prof. dr. ir. Martin van Ittersum, and to my other colleagues of the group of Plant Production Systems, for their great hospitality and friendship during my post-retirement period at the Wageningen University.

Bert Janssen Wageningen, March 2017

# Summary

## Crop yields and NPK use efficiency of a long-term experiment on a former sea bottom in the Netherlands

In the twentieth century, the ‘Zuyderzee’, an inland sea in the Netherlands, was closed off from the North Sea, and several ‘IJsselmeerpolders’ were created on the former sea bottom. In 1968, the Wageningen University decided to start an experimental farm in Oostelijk Flevoland, the Southeastern polder. The farm received the name ‘Ir. A.P. Minderhoudhoeve’ (APM). Although it was already known that the soils were very fertile, farmers and (soil) scientists lacked a sound scientific assessment of the time span with that high soil fertility status and ample soil reserves of P and K. Hence, the Soil Fertility group of the university designed a long-term $2^3$ NPK factorial experiment to examine how long it takes before the soil supplies of N, P and K get depleted when no nutrients are applied, and whether selected crop types respond differently to applied nutrients.

The experiment lasted for 28 years. During those years control yields did not decline. Yields were strongly correlated to winter rainfall (December-April). Therefore, yields were corrected for winter rainfall and adjusted to 305 mm of winter rains, being the average of the 28 years of the experiment. When no N, P or K was applied, yields were on average 70, 97 or 101%, respectively, of overall average yields. The yield response to P was significant in only a quarter of the experimental years and, averaged across all crops, about 8% of the yields of crops receiving no input of P (P0 yields). A response to K was never found. The response to N was on average about 60% of the N0 yields for sugar-beets, almost 70% for potatoes, 80% for winter-wheat and 110% for spring-barley. Winter rains influenced the N rates needed for maximum yield. The responses to N and P gradually increased which was ascribed to improved crop varieties with higher yield potentials, especially for sugar-beets. Even after 28 years, no P and K shortages were observed, confirming the soils’ reputation of being very fertile.

During six years, crops were chemically analysed to get a better understanding of the responses to N, P and K. The observed nutrient uptakes confirmed this polder soil to be poor in N, very rich in K and rich in P. The available amount of a nutrient in soil and input was estimated as the maximum uptake of the nutrient in situations in which the availability of that nutrient was the dominant growth-limiting factor. The ratio of available N to applied N, i.e. the availability fraction of applied N was more than 90%, but less in years after high winter rains. Calculated optimum N rates for

maximum N uptake often were beyond the actual rates applied in the trial. Application of K had no effect on the uptake of N while the input of P (IP) sometimes increased the uptake of N a little. In such cases, the effect of IP consisted of a direct effect of P and an indirect effect via stimulated uptake of N. Although P and K inputs hardly influenced yields, they clearly stimulated uptakes of P and K, resulting in luxury consumption of these nutrients. Estimated available fractions of P in IP were 25% for spring-barley, 24% for sugar-beets and 6% for potatoes. Estimated available fractions of K in IK were around 100% for sugar-beets and potatoes, and varied strongly for spring-barley. The extremely great availability fractions of fertilizer N and K were ascribed to upward movement of sub-soil moisture with easily dissolving nutrients during the growth season. Uptake efficiency of soil N as well as of input N was always very high. When no N was applied, large parts of available soil P and K were not taken up by the crops and remained unused.

Assessments were made of physiological use efficiency (PhE) of N, P or K, *i.e.* the ratio of yield to uptake by the crops, and of agronomic use efficiency (AE), of N, P or K, *i.e.* the ratio of yield to available supply by soil and input. For the appraisal of the balances among N, P and K, the quantities of N, P and K were expressed in units of crop nutrient equivalents (CNE). One (k)CNE was defined as the quantity of the nutrient that, under conditions of balanced nutrition, has the same effect on yield as one (k)g of N. The quantities of N, P and K, taken up or available, and expressed in units of CNE were added to ΣU (uptake) or to ΣA (available), and the fractions of N, P and K in ΣU or ΣA were calculated. Compared with maximum and minimum values from literature, the PhE values of N observed in the experiment were close to maximum, pointing to severe N limitation, but those of P and K were between medium and minimum, especially for spring-barley and sugar-beets. Potato was the only crop effectively using absorbed fertilizer P and K for additional yield. Soil supplies of available N, P and K were far from balanced, with average fractions of 10, 41 and 49%, respectively, of the sum of soil available N, P and K, expressed in CNE. Available N, P and K in soil and input together were optimally balanced at high inputs of N and no applications of P and K in the cases of sugar-beets and spring-barley, and at medium inputs of N in combination with P and especially K application in the case of potatoes. At these NPK inputs, the relative agronomic use efficiency of the sum of available N, P and K (ΣA) was 90% of the theoretically maximum value. It was calculated that spring-barley and sugar-beets needed only input of N (about 200 and 125 kg ha-1) to attain the water-limited yields of 8.5 Mg ha$^{-1}$ grain and 15 Mg ha$^{-1}$ root dry-matter, respectively. Potatoes required smaller than the standard inputs of N, and larger than the standard inputs of P and K for the water-limited tuber dry-matter production of 15 Mg ha$^{-1}$. In a rotation with cereals, sugar-beets and potatoes, application of P and K only to potatoes would suffice to continue cropping for another great, yet unknown number of years.

The uptakes of P and K from the soil alone (SUP and SUK) were compared with the uptakes of P and K required for balanced NPK nutrition ($UP_{bal}$ and $UK_{bal}$). Because for spring-barley and sugar-beets SUP proved greater than $UP_{bal}$ and SUK greater than $UK_{bal}$, positive yield responses by these crops to P and K input cannot be expected. In the case of potatoes, however, SUP or SUK were sufficient for tuber DM yields of not more than 4 to 5 Mg ha$^{-1}$. Some simple calculations on soil chemical data and crop uptake revealed that the stable soil pool of P is able to refill the labile P pool, and hence secure P uptake, likely for tens of years.

# Samenvatting

## Gewasopbrengsten en NPK gebruiksefficiëntie in een lange-termijn proef op een voormalige zeebodem in Nederland.

In de twintigste eeuw werd de Zuyderzee, een binnenzee in Nederland, afgesloten van de Noordzee, waarna verscheidene 'IJsselmeerpolders' werden gecreëerd op de voormalige zeebodem. In 1968 besloot de Wageningen Universiteit te beginnen met een proefboerderij in Oostelijk Flevoland, de zuidoostelijke polder. Het bedrijf kreeg de naam 'Ir. A.P. Minderhoudhoeve' (APM). Het was toen al bekend dat de bodems in de polder zeer vruchtbaar waren, maar boeren en bodemkundigen beschikten niet over wetenschappelijk goed onderbouwde kennis van de te verwachten tijdsduur van die hoge bodemvruchtbaarheid en ruime bodemvoorraden van P en K. Daarom diende de bodemvruchtbaarheidsgroep van de universiteit een voorstel in voor een lange-termijn $2^3$ NPK-factorenproef om na te gaan hoe lang het duurt voor de voorraden N, P en K in de grond uitgeput raken wanneer die nutriënten niet worden toegediend, en of verschillende gewassen verschillend reageren op toegediende nutriënten.

De proef duurde 28 jaren. In die periode gingen de controle-opbrengsten niet achteruit. Opbrengsten waren sterk gerelateerd aan de regenval in de voorafgaande wintermaanden (december-april). Daarom werden de opbrengsten gecorrigeerd voor een winterregenval van 305 mm, het gemiddelde van de regenval van december tot en met april gedurende de 28 jaren van de proef. Wanneer geen N, P of K werd toegediend waren de opbrengsten respectievelijk 70, 97 of 101% van de over alle acht bemestingsbehandelingen gemiddelde opbrengsten. De reactie op bemesting met P was slechts in een kwart van de proefjaren significant en gemiddeld voor alle gewassen ongeveer 8% van de opbrengsten verkregen zonder P bemesting. Nooit was de reactie op K bemesting significant. De meeropbrengsten door N-bemesting waren voor suikerbieten, aardappelen, wintertarwe en zomergerst respectievelijk ongeveer 60, bijna 70, 80 en 110% van de opbrengsten verkregen zonder N-bemesting. Winterneerslag beïnvloedde de grootte van de N-gift die nodig was voor maximale opbrengst. De meeropbrengsten door N en P namen geleidelijk toe wat werd toegeschreven aan verbeterde rassen met een hoger opbrengstpotentieel, speciaal voor suikerbieten. Zelfs na 28 jaren werden geen (serieuze) P en K tekorten gevonden, wat de reputatie van deze gronden zeer vruchtbaar te zijn bevestigde.

Gedurende zes jaren werden de gewassen chemisch geanalyseerd om de meeropbrengsten door N, P en K beter te kunnen begrijpen. De gevonden nutriënten-opnames bevestigden dat deze polder arm is aan N, zeer rijk aan K en rijk aan P. De beschikbaarheid van een nutriënt in bodem en input (meststof) werd geschat als de verkregen maximum opname van dat nutriënt in situaties waarin de beschikbaarheid van dat nutriënt de belangrijkste groei-beperkende factor was. De verhouding tussen beschikbaar N en toegediend N, *i.e.* de 'beschikbaarheidsfractie' van toegediend N, was groter dan 90%, behalve in de jaren met veel winterregen. De berekende optimum N-giften voor maximum N opname lagen vaak boven de werkelijke giften in de proef. Input van K had geen effect op de opname van N terwijl input van P (IP) soms de opname van N een weinig vergrootte. In dergelijke gevallen bestond het effect van IP uit een direct effect van P en - via de gestimuleerde opname van N - ook uit een indirect effect van P. Hoewel input van P en input van K nauwelijks van invloed waren op de gewasopbrengsten, stimuleerden ze duidelijk de opnames van P en K, wat leidde tot luxe-consumptie van deze nutriënten. Geschatte beschikbaarheidsfracties van P in IP waren 25% voor zomergerst, 24% voor suikerbieten en 6% voor aardappelen. Geschatte beschikbaarheidsfracties van K in IK waren rond 100% voor suikerbieten en aardappelen en varieerden sterk voor zomergerst. De extreem grote beschikbaarheidsfracties van input N en K werden toegeschreven aan opstijging van bodemvocht gedurende het groeiseizoen vanuit de diepere bodemlagen, met daarin de gemakkelijk oplosbare nutriënten. De opname-efficiëntie zowel van bodem- als van input-N was altijd zeer hoog. Wanneer geen N was toegediend, werden grote gedeeltes van beschikbaar bodem P en K niet opgenomen door het gewas en bleven onbenut.

Voorts werd de fysiologische gebruiksefficiëntie (PhE) van N, P en K bepaald, *i.e.* de verhouding van opbrengst tot opname door het gewas, en ook de agronomische gebruiksefficiëntie (AE), *i.e*. de verhouding van opbrengst tot de hoeveelheid van beschikbaar N, P en K in bodem en input. Voor de evaluatie van de balans tussen N, P en K (hun onderlinge verhoudingen) werden de hoeveelheden N, P en K uitgedrukt in eenheden van 'crop nutrient equivalents (CNE)'. Een (k)CNE was gedefinieerd als de hoeveelheid van het nutriënt die, bij gebalanceerde voeding, hetzelfde effect op de opbrengst heeft als een (k)g N. De in eenheden van CNE uitgedrukte hoeveelheden van opgenomen, respectievelijk beschikbare N, P en K werden opgeteld tot $\Sigma U$ (uptake) en $\Sigma A$ (available) en de fracties van N, P en K in $\Sigma U$ en $\Sigma A$ werden berekend. Vergeleken met de maximum en minimum waarden in de literatuur, lagen de in de proef gevonden PhE waarden van N dicht bij het maximum, wat wijst op ernstige N-beperking, maar die van P en K zaten tussen gemiddeld en minimum, in het bijzonder voor zomergerst en suikerbieten. Aardappel was het enige gewas dat effectief de opgenomen input-P en -K gebruikte voor extra opbrengst. De bodemvoorraden van beschikbaar N, P en K waren absoluut niet goed in balans, met gemiddelde fracties van 10, 41 and 49% van de som van beschikbaar bodem-N, -P en –K, uitgedrukt in CNE. Beschikbaar N, P en K in bodem en input samen waren het best in balans bij een grote input van N en geen toediening van P en K in het geval van suikerbieten en zomergerst, en bij een gemiddelde input van N in combinatie met P- en vooral K-toediening in het geval van aardappelen. Bij een dergelijke NPK input, was de relatieve agronomische gebruiksefficiëntie van de som van beschikbaar N, P en K in bodem en input (ΣA) gelijk aan 90% van de theoretisch maximale waarde. Uit berekeningen volgde dat zomergerst en suikerbieten alleen een input van N nodig zouden hebben (ongeveer 200 en 125 kg $ha^{-1}$) om de water-beperkte graanopbrengst van 8.5 Mg $ha^{-1}$ en de water-beperkte wortelopbrengst van 15 Mg $ha^{-1}$ (droge stof) te bereiken. Aardappelen vroegen geringere dan de standaard input van N, en grotere dan de standaard input van P en van K voor de water-beperkte knolproductie (droge stof) van 15 Mg $ha^{-1}$. In een rotatie met granen, suikerbieten en aardappelen zouden P en K alleen aan aardappelen toegediend hoeven te worden voor een voortgezette productie gedurende wederom een groot, maar nog steeds onbekend, aantal jaren.

De opnames van P en K uit de bodem alleen (SUP en SUK) werden vergeleken met de gewasopnames van P en K die vereist zijn voor gebalanceerde NPK voeding ($UP_{bal}$ en $UK_{bal}$). Omdat voor zomergerst en suikerbiet SUP groter bleek dan $UP_{bal}$ en SUK groter dan $UK_{bal}$, kan bij deze gewassen geen positieve opbrengstreactie op P of K input worden verwacht. In het geval van aardappelen waren SUP en SUK echter slechts voldoende voor knolopbrengsten (droge stof) van niet meer dan 4 tot 5 Mg $ha^{-1}$. Enkele eenvoudige berekeningen over chemische bodemgegevens en gewasopname brachten aan het licht dat de stabiele pool van bodem-P gedurende waarschijnlijk tientallen jaren de labiele pool van bodem-P kan aanvullen, en dus de opname van P door het gewas veilig kan stellen.

# List of Acronyms

| | |
|---|---|
| AE | Agronomic use efficiency |
| AEΣA | Agronomic use efficiency of the sum of available N, P and K, expressed in kg $kCNE^{-1}$ |
| $AE\Sigma A_{max}$ | Maximum value of AEΣA, expressed in kg $kCNE^{-1}$ |
| $AF_I$ | Availability fraction of input nutrients |
| $AF_{IK}$ | Availability fraction of input K |
| $AF_{IN}$ | Availability fraction of input N |
| $AF_{IP}$ | Availability fraction of input P |
| AK | Available K |
| $AK_{bal}$ | Available K required for balanced NPK nutrition |
| AN | Available N |
| $AN_{bal}$ | Available N required for balanced NPK nutrition |
| $AN_{N0}$ | Available N at N0 |
| $AN_{NH}$ | Available N at NH |
| $AN_{NL}$ | Available N at NL |
| AP | Available P |
| $AP_{bal}$ | Available P required for balanced NPK nutrition |
| APM | Ir. A.P. Minderhoudhoeve |
| B | Biomass |
| $b_N$ | Regression coefficient of linear term in YNP equation (Eq.A.4.2.a) |
| $b_P$ | Regression coefficient of linear term in YPN equation (Eq.A.4.2.b) |
| CF | Factor to convert kg into kCNE |
| CFK | Conversion factor of K |
| CFP | Conversion factor of P |
| $c_N$ | Regression coefficient of quadratic term in YNP equation (Eq.A.4.2.a) |
| CNE | Crop nutrient equivalent |
| $c_P$ | Regression coefficient of quadratic term in YPN equation (Eq.A.4.2.a) |
| CV | Coefficient of variation |
| $E_{max}$ | Maximum value of nutrient use efficiency |

| | |
|---|---|
| $E_{min}$ | Minimum value of nutrient use efficiency |
| $e_N$ | $(PhEN_{max} – PhEN_{med})/PhEN_{med}$ or<br>$(PhEN_{med} – PhEN_{min})/PhEN_{med}$ (e stands for extreme) |
| $e_P$ $e_K$ $e_1$ $e_2$ | See $e_N$ |
| FK | Fraction of K in ΣU or in ΣA |
| FN | Fraction of N in ΣU or in ΣA |
| FP | Fraction of P in ΣU or in ΣA |
| FΣSA | Fractions of nutrients in the sum of soil available N, P and K |
| HI | Harvest index |
| IA | Input of available nutrients |
| $IAK_{kCNE}$ | Input of available K, expressed in kCNE |
| IAN | Input of available N |
| $IAN_{kCNE}$ | Input of available N, expressed in kCNE |
| $IAP_{kCNE}$ | Input of available P, expressed in kCNE |
| IK | Input of K, available and not-available |
| IN | Input of N, available and not-available |
| INMAX | Input of N required for maximum yield |
| $IN_{NH}$ | Input of N at NH |
| $IN_{NL}$ | Input of N at NL |
| $IN_{opt}$ | Optimum input of N |
| INWR | Recommended N input rates as based on winter rains |
| IP | Input of P, available and not-available |
| kCNE | Kilo crop nutrient equivalent |
| K-HCl | Soil K, extracted with 0.1 M HCl and 0.4 M oxalic acid |
| MF | Mass fraction |
| $MFK_{max}$ | Maximum mass fraction of K |
| $MFK_{min}$ | Minimum mass fraction of K |
| $MF_{max}$ | Maximum mass fraction |
| $MF_{min}$ | Minimum mass fraction |
| $MFN_{min}$ | Minimum mass fraction of N |
| MFP | Mass fraction of P |
| $MF_s$ | Mass fraction in stover (economically not interesting parts of a crop) |

| | |
|---|---|
| $MF_y$ | Mass fraction in yield (economically interesting parts of a crop) |
| m | $PhE_{med}$ |
| $m_N$ | $PhEN_{med}$ |
| Mn35A | Code of mapping unit of the soil at Minderhoudhoeve |
| N1 | Recommended N input rates as based on soil mineral N |
| NH | Treatments receiving 133% of N1 |
| NL | Treatments receiving 67% of N1 |
| P0K0 | Treatments receiving no P and no K |
| P0K1 | Treatments receiving no P and standard quantity of K |
| P1K0 | Treatments receiving standard quantity of P and no K |
| P1K1 | Treatments receiving standard quantities of P and K |
| PhE | Physiological use efficiency, expressed in kg $kg^{-1}$ |
| $PhE_{max}$ | Maximum (value of) physiological use efficiency |
| $PhE_{med}$ | Medium (value of) physiological use efficiency |
| $PhE_{min}$ | Minimum (value of) physiological use efficiency |
| PhEK | Physiological use efficiency of K |
| $PhEK_{max}$ | Maximum (value of) physiological use efficiency of K |
| $PhEK_{med}$ | Medium (value of) physiological use efficiency of K |
| $PhEK_{min}$ | Minimum (value of) physiological use efficiency of K |
| $PhEN_{max}$ | Maximum (value of) physiological use efficiency of N |
| $PhEN_{med}$ | Medium (value of) physiological use efficiency of N |
| $PhEN_{min}$ | Minimum (value of) physiological use efficiency of N |
| $PhEP_{max}$ | Maximum (value of) physiological use efficiency of P |
| $PhEP_{med}$ | Medium (value of) physiological use efficiency of P |
| $PhEP_{min}$ | Minimum (values of) physiological use efficiency of P |
| PhEΣU | Physiological use efficiency of the sum of N, P and K taken up, expressed in kg $kCNE^{-1}$, |
| PPO | Praktijkonderzoek Plant & Omgeving (Applied Research Plant & Environment |
| QUEFTS | Quantitative Evaluation of the Fertility of Tropical Soils |
| RAEΣA | Relative AEΣA |
| $r_{av}$ | Rainfall of December-April, averaged across all cropping years (1975-2002) |

| | |
|---|---|
| $r_i$ | Rainfall of December-April in year i |
| RE | Relative efficiency of nutrient use |
| $RF_{IP}$ | Recovery fraction of input P |
| $RF_{NL}$ | Recovery fraction of IN at NL |
| RMSE | Root of mean square error |
| RPhE | Relative physiological nutrient use efficiency |
| RPhEK | Relative physiological use efficiency of K |
| RPhEN | Relative physiological use efficiency of N |
| RPhEP | Relative physiological use efficiency of P |
| RPhEΣU | Relative physiological efficiency of the sum of N, P and K taken up |
| RUE | Relative uptake efficiency |
| S | Stover (economically not interesting parts of a crop) |
| SA | Soil available supply (= maximum uptake from soil) |
| SAK | Soil available K |
| $SAK_{kCNE}$ | Soil available K, expressed in kCNE |
| SAN | Soil available N |
| $SAN_{kCNE}$ | Soil available N, expressed in kCNE |
| SAP | Soil available P |
| $SAP_{kCNE}$ | Soil available P, expressed in kCNE |
| SD FΣA | Standard deviation of the fractions of N, P and K in ΣA |
| SD FΣU | Standard deviation of the fractions of N, P and K in ΣU |
| SPSS-19 | Statistical Package |
| SUK | K uptake from soil alone |
| SUP | P uptake from soil alone |
| TY | Target yield |
| U | Crop uptake (of nutrients) |
| UE | Uptake efficiency |
| UEK | Uptake efficiency of K |
| $UE_{max}$ | Maximum (value of) uptake efficiency |
| $UE_{min}$ | Minimum (value of) uptake efficiency |
| UEN | Uptake efficiency of N |

| | |
|---|---|
| UEP | Uptake efficiency of P |
| UK | Uptake of K |
| $UK_{kCNE}$ | Uptake of K, expressed in kCNE |
| UN | Uptake of N |
| $UN_{kCNE}$ | Uptake of N, expressed in kCNE |
| $UN_m$ | Uptake of N for maximum or minimum yield |
| $UN_{max}$ | Maximum UN in equations calculating $b_N$ and $c_N$ |
| $UN_{min}$ | Minimum UN in equations calculating $b_N$ and $c_N$ |
| UP | Uptake of P |
| $UP_{kCNE}$ | Uptake of P, expressed in kCNE |
| $UP_{max}$ | Maximum UP in equations calculating $b_P$ and $c_P$ |
| $UP_{min}$ | Minimum UP in equations calculating $b_P$ and $c_P$ |
| WR | Winter rain, rainfall from December to April in mm |
| Y | (Dry) mass of the economically interesting parts of a crop |
| Y12 | Yield calculated as function of U1 (along X-axis) and U2 |
| Y21 | Yield calculated as function of U2 (along X-axis) and U1 |
| YIA or Y2A | Yields at maximum accumulation of nutrient 1 or 2 |
| YID or Y2D | Yields at maximum dilution of nutrient 1 or 2 |
| $y_{iadj}$ | Yield in year (i) adjusted to average winter rainfall |
| $y_{imea}$ | Measured yield in year (i) |
| YINWR | Yields calculated with an equation relating yield to INWR |
| $y_{ir}$ | Yield calculated in relation to $r_i$ |
| YMAX | Maximum yield |
| YNA | Yields at maximum accumulation of N (notation in Janssen et al., 1990) |
| $Y_N^a$ | Yield at maximum accumulation (notation in Sattari et al., 2014) |
| YND | Yields at maximum dilution of N (notation in Janssen et al., 1990) |
| $Y_N^d$ | Yield at maximum dilution of N (notation in Sattari et al., 2014) |
| YNP | Yield calculated as function of UN (along X-axis) and UP |
| $Y_P^a$ | Yield at maximum accumulation of P (notation in Sattari et al., 2014) |
| $Y_P^d$ | Yield at maximum dilution of P (notation in Sattari et al., 2014) |
| YPD | Yields at maximum dilution of P (notation in Janssen et al., 1990) |

| | |
|---|---|
| YPN | Yield calculated as function of UP (along X-axis) and UN |
| $y_{rav}$ | Yield corresponding with $r_{av}$ |
| $Y/UK_{kg\ med}$ | $PhEK_{med}$ |
| $Y/UN_{kg\ med}$ | $PhEN_{med}$ |
| $Y/UP_{kg\ med}$ | $PhEP_{med}$ |
| $\Delta UP$ | $\Delta UP_{(P1-P0)} + \Delta UP_{(UN)}$ |
| $\Delta UP_{(P1-P0)}$ | Difference in P uptake between P1 and P0 at the same N uptake |
| $\Delta UP_{(UN)}$ | Difference in P uptake related to difference in N uptake |
| $\Delta Y_{(P1-P0)}$ | Difference in yield between P1 and P0 at the same N uptake |
| $\Delta Y_{(UN)}$ | Difference in yield related to difference in N uptake |
| $\Sigma A_{kCNE}$ | Sum of available N, P, and K in soil and input, expressed in kCNE |
| $\Sigma IA_{kCNE}$ | Sum of available N, P, and K in input, expressed in kCNE |
| $\Sigma_{opt}$ AK | Optimum supply of available K in soil and input |
| $\Sigma_{opt}$ AN | Optimum supply of available N in soil and input |
| $\Sigma_{opt}$ AP | Optimum supply of available P in soil and input |
| ΣSA | Sum of soil available N, P and K |
| $\Sigma SA_{kCNE}$ | Sum of soil available N, P, and K expressed in kCNE |
| $\Sigma U_{kCNE}$ | Sum of (actual) uptake of N, P, and K, expressed in kCNE |
| $\Sigma UK_{bal}$ | Sum of K uptake from soil and input at balanced nutrition |
| $\Sigma UN_{bal}$ | Sum of N uptake from soil and input at balanced nutrition |
| $\Sigma UP_{bal}$ | Sum of P uptake from soil and input at balanced nutrition |

# Index

**Z**

# List of Figures

# List of Tables

# Table of Contents

# Chapter 1

# General introduction and background of research

### Highlights

- Several 'IJsselmeerpolders' were created between 1944 and 1968, a.o. Southeastern polder (Oostelijk Flevoland) in 1957.
- In Oostelijk Flevoland, it was examined during a long-term experiment comprising 28 cropping seasons how long it would take before the soil becomes depleted of N, P and K when no nutrients were applied.

## 1.1. History of polders in the Netherlands

Since the Middle-Ages, the Dutch have been reclaiming land from swampy areas, coastal zones and lakes. During the 19$^{th}$ century, larger areas, under still deeper water, were reclaimed among others to prevent flooding. In the Dutch tradition, building dikes was not alone for safety reasons, but even more to regain land from the sea. In general, the soils of the reclaimed land proved to be very productive allowing excellent conditions for arable farming. The first plans to reclaim the Southern Sea (Zuyderzee) and to connect the Wadden Islands by dikes were already made in the 17$^{th}$ century. Plans developed in the 19$^{th}$ century were more realistic. A flood disaster around the Zuyderzee in 1916 was the final trigger to decide that the Zuyderzee would be enclosed and the land reclaimed (Hermsen, 1988). In 1932, the big dam (Afsluitdijk) was completed. The closed off Zuyderzee was subsequently renamed as IJsselmeer (lake at the end of the river IJssel). The salt-water Zuyderzee gradually changed into a fresh-water lake receiving its water from the river 'IJssel', which is the northern branch of the river Rhine. To develop expertise first a small pilot project 'Polder Andijk' (40 ha) was completed, followed by the polder Wieringermeer (20,000 ha) in the Northwest part of the Zuyderzee (Figure 1). Based on the positive experiences, plans to reclaim larger polders were developed. Various dikes were built to create polders and control the water level by facilitating pumping of the water. In this way, several 'IJsselmeerpolders' were created: Northeast polder (Noordoostpolder; 57,000 ha) in 1944, Eastern polder (Oostelijk Flevoland; 54,000 ha) in 1957, and Southern polder (Zuidelijk Flevoland; 43,000 ha) in 1968.

## 1.2. Land reclamation, soil and crop research

After the land stood clear of the water, it took about eight years to drain the muddy land, grow reed (*Phragmites*) to promote soil ripening and to convert the mud into arable land. The first crops planted (*e.g*. rapeseed) had some tolerance to salinity in the deeper soil layers. Already in the early stages of land reclamation, the consequences of the transformation of the land from salt to fresh water conditions for the physicochemical soil processes were studied (Zuur, 1938). Long-term experiments started in the 1950's a.o. at the Lovinkhoeve, an experimental farm in the Northeast Polder (Kooistra et al., 1989). Since the 1970's, the IJsselmeerpolders became internationally known as an area with very fertile soils, modern farming and superior crop productivity. The quality of the land in Oostelijk Flevoland attracted not only the interest of farmers' organizations, but also of private companies (e.g., breeders) and governmental institutions. Various agricultural research institutes, research stations and experimental farms were established. The relatively homogeneous and fertile soils created favourable conditions for field experiments.

Wageningen University too took initiatives to establish an experimental facility for research and education in Oostelijk Flevoland. In 1968, it was decided to start 'Proefbedrijf Flevoland' (PFL), an experimental farm with arable and grazing land near Swifterbant (Kloosterman, 1975). Some years later, it was renamed as 'A.P. Minderhoudhoeve' (Burrough et al., 1985). Since 1995, an extensive program of Mixed Farming Systems Research was carried out at the Minderhoudhoeve (Lantinga & Van Laar. 1997), but the long-term soil fertility experiment was no part of it.

## 1.3. Soil fertility studies by Wageningen University

In 1974, the then department of 'Agricultural Chemistry' of the university made plans for a long-term study of changes in the soil supply of crop nutrients. The main question was how long it takes before the soil gets deficient in the main nutrients nitrogen (N), phosphorus (P) and potassium (K). A second question was whether selected crop types respond differently to applied nutrients. The reclaimed soils were rich in calcium carbonate (10%) from seashell fragments, magnesium and potassium and moderately rich in phosphorus. It was stated that application of fertilizers, even of nitrogen, initially was hardly needed when the soils developed on the sediments of the former 'Zuyderzee' came into crop production (Jonker, 1960; Ente et al., 1986). After some years of cropping, however, yields increased upon application of nitrogen.


**Fig. 1.** Zuyderzee polders. A.P. Minderhoudhoeve is at about 15 km northeast of Lelystad.

Farmers and (soil) scientists lacked a sound scientific assessment of the time span with high soil fertility status and ample soil reserves of P and K. Hence, it was decided to study how long crop yields will be maintained without application of fertilizer nutrients. Such a study was also considered useful for students in soil science or crop production at Wageningen University. The actual fieldwork started in 1975 with sugar-beets as the first crop in a four-year rotation of sugar-beets, spring-barley, potatoes, and winter-wheat. The long-term experiment ran from 1975 to 2002, comprising 28 cropping seasons. After 2002, the experiment ended when the university closed the experimental farm.

It took quite some time to organize and publish the experimental data. Moreover, some novel approaches on nutrient use efficiencies had first to be developed before they could be applied. So far, preliminary results were presented in internal reports (e.g. Slangen & Menkveld, 1982) and in a conference paper (Janssen & Menkveld, 1998). Some information on nutrient use efficiency in this experiment was provided in an article on balanced supplies of crop available nutrients (Janssen, 2011).

The next two chapters are seen as the final report on the long-term experiment. Chapter 2 deals with variations in yields during the 28 years and answers the first and second question. In Chapter 3, N, P and K availability in soil and input are determined and nutrient uptake and uptake efficiency by the crops that were chemically analysed (years 1994-1999), are discussed. Chapters 4 and 5 form a reflection on the results presented in Chapters 2 and 3. Chapter 4 combines yield and uptake data to assess and examine physiological and agronomic nutrient use efficiencies; it introduces a method for the study of the balance (or equilibrium) among available N, P and K in soil and input, by applying the concepts of crop nutrient equivalents; and it utilizes the method and concepts to build a framework for recommendations on nutrient input required for target yields with balanced NPK nutrition. Chapter 5 tries to explain why the crop responses to NPK in this long-term experiment were as they were, and synthesizes the results and conclusions.

# Chapter 2

# Crop yields in relation to N, P, and K applications, and to winter rainfall


## Abstract

This chapter describes the results of a 28 years field experiment (1975 - 2002) at the 'Ir. A.P. Minderhoudhoeve', the experimental farm of Wageningen University in the polder Oostelijk Flevoland. The objectives were to study how long it would take before the soil falls short in N, P and K, and whether crops would respond differently to applied nutrients. Sugar-beets, spring-barley, potatoes, and winter-wheat were grown in a four-year rotation on a calcareous Entisol with about 30% clay and 10% $CaCO_3$. From 1975 to 1993 the experimental design was a $2^3$ NPK factorial in 3 replicates and from 1994 to 2002 a 3 N · $2^2$ PK factorial in two replicates. Yields were strongly correlated to winter rainfall (December-April). Therefore, yields were corrected for winter rainfall and adjusted to the long-term average of 305 mm winter rains. From the first year onwards, all crops responded sharply to N application. The response to N was on average about 60% of the N0 yields for sugar-beets, almost 70% for potatoes, 80% for winter-wheat and 110% for spring-barley. Winter rains influenced the N rates needed for maximum yield. The average yield response to P was about 8% of P0 yields for all crops, while never a response to K was found. Although N0 and P0 yields did not change during the study, the responses to N and P gradually increased. This rise was ascribed to improved crop varieties with higher yield potentials, especially for sugar-beets. Even after 28 years, no P and K shortages were observed, confirming the soils' reputation of being very fertile.


## Highlights

- When no N, P or K was applied, yields were 70, 97 or 101%, respectively of the yields averaged across all treatments.
- Yields were negatively correlated to preceding winter rainfall.
- N application required for maximum yield was related to winter rainfall.
- N application recommendations simply based on winter rainfall were 12% higher than recommendations based on soil mineral N, but the corresponding yields were only 0.5% higher.

- During 28 years, control yields did not decline.
- Sugar-beets and potatoes showed increasing responses to nitrogen and phosphorus in the course of the experiment because of improved crop varieties, but spring-barley did not.

**Keywords:** calcareous Entisol, IJsselmeerpolder, sugar-beets, spring-barley, potatoes, winter-wheat

## 2.1. Introduction

In 1974, the then department of ‘Agricultural Chemistry’ of the Wageningen university initiated plans for a long-term study of changes in the soil supply of crop nutrients. Specific questions were how long it will take before the soil of the Flevopolder gets deficient in N, P and K, and whether selected crop types respond differently to applied nutrients. The reclaimed soils were known to be rich in calcium carbonate (10%) from seashell fragments, magnesium and potassium, and moderately rich in phosphorus. It was stated that application of fertilizers, even of nitrogen (N), was hardly needed when the soils developed on the sediments of the former ‘Zuyderzee’ (Southern Sea) came into crop production (Jonker, 1960; Ente et al., 1986). After some years of cropping, however, a yield increase of winter wheat was reported from 6400 to 8210 kg $ha^{-1}$ for application rates of 50 and 200 kg N $ha^{-1}$, respectively (Spiertz & Ellen, 1978). Responses to potassium (K) had not yet been observed around 1975, while most crops did respond to fertilizer phosphorus (P) (Kloosterman, 1975).

Farmers and (soil) scientists lacked a sound scientific assessment of the time span with high soil fertility status and ample soil reserves of P and K. Hence, it was decided to study how long crop yields will be maintained without application of fertilizer nutrients. Such a study was considered useful also for students in soil science or crop production at Wageningen University. The actual field work started in 1975 with sugar-beets as the first crop in a four-year rotation of sugar-beets, spring-barley, potatoes, and winter-wheat. The long-term experiment ran from 1975 to 2002, comprising 28 cropping seasons. After 2002, the experiment ended when the university closed the experimental farm.

This chapter reports on the annual yield responses to various N, P and K applications during successive years of the long-term experiment in comparison to controls. The original hypothesis was that the responses would steadily increase because the soil in the non-fertilized control plots would gradually become exhausted. Another objective was to understand the among years variation in

responses to N, P and K, by taking the weather conditions, especially winter rainfall, into account.
Because effects of applied nutrients could also change as a consequence of improved crop varieties utilizing available nutrients in a more efficient way, it was also examined whether changing responses to fertilizer nutrients were related to trends in crop potentials or to diminishing soil fertility or to both.

## 2.2. Materials and methods

### *2.2.1. Soil characteristics and cropping systems*

The soils of the Minderhoudhoeve (mapping unit Mn35A) were identified as 'kalkrijke poldervaaggronden' (calcareous Entisols) with a texture of loam to clay loam (25-35% clay), and were considered as very fertile and very suitable for arable crops (Eilander et al., 1990). Drainage had started in 1960. From 1960 to 1974, the field was successively planted to crops, which cumulatively received 550 kg N, 180 kg P and no K.

On the experimental site, the soil initially contained 16 g kg $^{-1}$ soil organic carbon (SOC), 106 g kg $^{-1}$ $CaCO_3$, and had a pH(KCl) of 7.3. At the start of the experiment in 1975, P-water was 26 mg $P_2O_5$ per litre, and K-HCl was 17 mg $K_2O$ per 100 g (see Section 2.3.1).

At the Ir. A.P. Minderhoudhoeve (henceforth abbreviated to APM), sugar-beets, spring-barley, potatoes, and winter-wheat were grown in a four-year rotation since 1967. Sometimes weather and wet soil conditions made it impossible to sow the crop; then the management decided to grow another crop. Hence, the long-term experiment of 28 years did not consist of seven complete cycles, but of six only. The intended rotation crop was postponed in Cycles 2, 4 and 5; instead, in-between crops were grown: flax (1981), spring-wheat (1990), and silage maize (1996 and 1997). Winter-wheat was grown in four cycles only, because it was two times replaced: in 1998 by spring-barley and in 2002 by spring-wheat. As a result, of these replacements spring-barley was grown seven times during the experiment.

### *2.2.2. Experimental layout and fertilizer applications*

From 1975 to 1993, the experimental design was a $2^3$ NPK factorial, with and without applications of N, P and K, in 3 replicates. The allocation of treatments to the experimental units remained the same in this period. Application rates of N were fixed during Cycles 1 and 2, and those of P and K were fixed throughout the experiment, following the standard practices of the A.P. Minderhoudhoeve. The fertilizers used were $Ca(NO3)_2$ with 15.5% N, triple-superphosphate with 19% P, and potassium sulphate with 41.5% K (potatoes) or KCl with 31% K (other crops). The rates of P were 87 for potatoes, 65 for sugar-beets, 44 for flax, 35 for maize, 31 for winter-wheat and 25 kg ha$^{-1}$ for spring-barley and spring-wheat. The rate of K was 41 kg ha$^{-1}$ for all crops, with the exceptions of flax (83) and silage maize (62). (Note: P and K are expressed as elements). In Cycles 1 and 2, N application rates were set at 210 kg for potatoes, 150 for sugar-beets, 57.5 for wheat and barley, and 15 for flax. From Cycle 3 (Year 1984) onwards, the recommended doses of N (N1) were based on soil mineral N analyses, usually sampled in February-March, and an estimate of the expected yield (Neeteson, 1995) and, hence, N1 varied among the years (Table 2.3). In 1994, the experimental design was changed into a 3 N · $2^2$ PK factorial. This modification was made because N1 seemed below optimum. Consequently, the original 3 replicates had to change into 2 replicates, denoted by A and B in Table 2.1. Plots 9, 11, 13 and 16 of the original Replicate 2 were considered to belong to the new Replicate A and Plots 10, 12, 14 and 15 to the new Replicate B (Table 2.1). Treatments with low N (NL), presented in italics in Table 2.1, were all in plots receiving N1 before 1994. Treatments with high N (NH) are in bold; half of them were in plots receiving N0, and half in plots receiving N1 before 1994. The NL and NH application rates (Table 2.1) were adjusted to a level of 67 and 133%, respectively, of the recommended N application N rate (N1 = 100%) based on soil mineral N.

**Table 2.1**
Layout of the experimental field and allocation of treatments before and since 1994. The bold codes H refer to treatments with high N, receiving 133% of the recommended N application (N1 = 100%), and the codes in italics (*L*) refer to treatments with low N, receiving 67% of N1. Replicates from 1 to 3, and crop rows were positioned approximately west to east. Replicates 3 to 1 roughly from north to south.

| **Replicate** | | ***Period 1975-1993*** | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 3 | Plot nr | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| | Treatment | 100 | 110 | 111 | 001 | 101 | 010 | 000 | 011 |
| 2 | Plot nr | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 |
| | Treatment | 000 | 001 | 011 | 010 | 110 | 111 | 100 | 101 |
| 1 | Plot nr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| | Treatment | 111 | 010 | 100 | 011 | 101 | 000 | 110 | 001 |
| | | ***Period 1994-2002*** | | | | | | | |
| B | Plot nr | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| | Treatment | *L00* | **H10** | *L11* | 001 | **H01** | 010 | 000 | **H11** |
| | Plot nr | 9 | | 11 | | 13 | | | 16 |
| | Treatment | **H00** | | 011 | | *L10* | | | *L01* |
| A | Plot nr | | 10 | | 12 | | 14 | 15 | |
| | Treatment | | 001 | | **H10** | | *L11* | *L00* | |
| | Plot nr | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 |
| | Treatment | **H11** | 010 | **H00** | 011 | *L01* | 000 | *L10* | **H01** |

To be able to compare the yields obtained in years before and since 1994 at a same N level, yields of sugar-beets, spring-barley and potatoes were calculated that would have been obtained at N1, respectively, using parabolic regression equations between yield (y) and N applications. For the period from year 20 to 28, parabolic regression equations between yields (y) and N applications rate (x) were assessed: $y = a \cdot x^2 + b \cdot x + c$, for x = 0 at Control, and x = 2/3 at NL and x = 4/3 at NH. Next the yield for x = 1 was calculated to represent yield at N1.This was done for each of the four PK combinations: P1K1, P1K0, P0K1, P0K0.

*2.2.3. Crop management and sampling*

The total size of a plot including border strips was 6 by 36 m, of which an area of 3 by 30 m was harvested to determine yield; an area of only 9 $m^2$ was harvested separately for assessments of harvest index and (in some years) chemical composition.

At harvest, grain and straw of cereal crops were removed from the field, potato haulms remained in the field, while sugar-beet leaves were sometimes removed and sometimes worked into the soil. The technical staff of the experimental farm carried out the standard farming practices, such as ploughing, sowing and harvesting, while the technical staff of the then department of Agricultural Chemistry of Wageningen University was responsible for the manual application of the fertilizers and the harvest of the net 9 $m^2$ sample areas. Samples of the crops grown in the period 1994-1999 were dried and chemically analysed at that department according to standard procedures (Temminghoff & Houba, 2004).

Yields of sugar-beets and potatoes are presented as dry matter (DM) yield of roots and tubers, respectively. In the experimental period, the average dry matter fraction of potato tubers was 25.9 % in the treatments without N and 23.4 % in the treatments with N. For sugar-beet roots, these fractions were 24.4 and 23.9%, respectively. Grain yields refer to grains with a moisture fraction of 15%.
Unfortunately, a part of the information on decisions taken by the manager of the experimental farm, such as planting dates, crop varieties, time of harvest, soil analyses was not saved, which hampered the investigation of their impacts on yields.

*2.2.4. Statistical analyses and data presentation*

We start with the calculation of a 28-years average yield obtained per fertilizer treatment relative to the average yield of the eight (2N · 2P · 2K) treatments; as explained above, NL and NH yields were combined into N1 yields. Statistical analyses were carried out on the data of each individual year with a SPSS-19-package, testing the main effects of replicates, N, P and K, and NP interaction.

Because the response to K was not significant, in further examinations the means of yields obtained at K0 and K1 were used, resulting in four treatment combinations (N1P1, N1P0, N0P1, N0P0). Data denoted by N1 are averages of N1P1 and N1P0, and data denoted by N0 are averages of N0P1 and N0P0. Similarly, data denoted by P1 data are averages of N1P1 and N0P1, and data denoted by P0 data are averages of N1P0 and N0P0. The thus found yield data were averaged across three (in years 1-19) or two (in years 20-28) replicates. These mean yields were utilized for the study of time trends in the effects of N and P. For the period from year 20 to 28, parabolic regression equations between yields (y) and N applications (x) were assessed, as explained in Section 2.2.2, for the calculation of y at x = 1. These parabolic equations were also used to assess the N input (INMAX) at which the yield is maximum (YMAX). INMAX was found by setting the first derivative ($dy/dx = 2ax + b$) at 0: INMAX = $-b/2a$. When $a$ had a negative value, INMAX was positive, and was used to calculate YMAX, provided that INMAX was within the range of the experimental values of x.

### *2.2.5. Weather conditions as co-variables*

Data on rainfall, temperature and radiation were collected and used to study their relation to yield variation among years. Meteorological data were measured at the APM itself until the on-farm installation was destroyed by a flash of lightning in the 1980's. Therefore, we had to use data from nearby stations instead. Daily rainfall data of the period 1975 – 2002 were available from a meteorological station in Swifterbant, at a distance of about 8 km. Data on radiation were only partly available. Data from 1976 to 1988 were obtained from the archives of the Applied Plant Research (Dutch abbreviation PPO) located in Lelystad at about 10 km from the experimental site. Since 1990, data from the official meteorological station at Lelystad airport, at a distance of about 20 km, were used. Temperature data were used from the central Netherlands meteorological institute at De Bilt, at a distance of about 80 km from APM.

As soil available N is low after wet winters as a result of leaching, it is to be expected that yields are related to rainfall in winter, especially when no N is applied. Long-term evidence indicated that N response increased with rainfall in the preceding winter, *e.g.* from November up to and including February (Van der Paauw, 1962; Ris et al., 1981). In the past, N fertilizer recommendations were based on that evidence. In this study, such relationships were examined for the crops of which at least six yields were available (sugar-beets, spring-barley and potatoes), by plotting measured yields ($y_{mea}$) against rainfall (r) during a certain interval in winter. Linear regression equations were assessed: $y = b \cdot r + a$. The choice of the most suited interval for winter rainfall (r) was based on a set of regression equations of yield to winter rainfall. For each of the possible intervals of two to seven consecutive months between November and May such calculations were made. The interval that gave the highest values of R-square of the regression equation was used for adjustment of yields to a certain standard winter rainfall. The best interval for sugar-beets and spring-barley was found to be December up to and including April, and for potatoes February- March. Because potato yields were also strongly related to the rainfall in the interval December-April, we decided to use the mean rainfall of December-April averaged across all (1975-2002) cropping years ($r_{av}$) as the standard amount of winter rainfall for all crops. The standard ($r_{av}$) was 305 mm. For each year (i) in which the crop under study was grown, regression equations of yields in relation to $r_i$ ($y_{ir}$) were calculated: $y_{ir} = b \cdot r_i + a$. This was done for each of the treatment combinations N1P1, N1P0, N0P1, N0P0 (see Appendix 2, Figure A.2.1). Further the yield ($y_{rav}$) corresponding with the average rain ($r_{av}$) was calculated: $y_{rav} = b \cdot r_{av} + a$. The difference ($y_{ir} - y_{rav}$) was used to adjust yields to the average rainfall: $y_{iadj} = y_{imea} - (y_{ir} - y_{rav})$, where $y_{iadj}$ and $y_{imea}$ stand for adjusted and measured yield, respectively, in year (i). It was envisaged that the variances among the years of $y_{iadj}$ were smaller than those among $y_{imea}$, and would thus assist the appraisal of time trends in the effects of N and P.

## 2.3. Results

### *2.3.1. Soil characteristics and fertility*

Soils were sampled and analysed at the start of the experiment in 1975, and in 1983. Table 2.2 presents information on soil extractable P and K. In the Netherlands, fertilizer P recommendations are based on Pw, a 1:60 (volume) extraction with water of 20 $^oC$. Fertilizer K recommendations are based on a so-called K-number. For marine clays the relation is (Van Dijk & Van Geel, 2010):
K-number = (K-HCl · b)/(0.15 · pH-KCl – 0.05).
K-HCl is found after a 1:10 (mass) extraction with 0.1 M HCl and 0.4 M oxalic acid. For the soil of this experiment, b = 0.954 and the denominator is 1 because pH-KCl must be set at 7 when it is above 7.

After eight years, in P1 plots where P had been applied annually, P-water was somewhat above the level before the start of the experiment, but in the plots where no P was applied P-water was halved (Table 2.2). It means that the fertilizer P recommendation for unfertilized soil was 45 to 55 kg $P_2O_5$ higher in 1983 than at the start of the experiment. Application of K hardly affected extractable soil potassium status. After eight crops, soil K-HCl was higher than at the start in 1975 for unknown reasons. Soil P and K levels of the fertilized plots were so high in 1983 that for cereals no application of P and K would be recommended.

### *2.3.2. General pattern of yield responses to N, P and K*

Figure 2.1 shows the relative yields, averaged over the whole period (28 years) in relation to fertilizer treatment. In each year, the average of the measured yields of the eight fertilizer treatments was set at 100%. The average yields of treatments without N (0, K, P, PK in Figure 2.1) and with N (N, NK, NP, NPK) were 70% and 130%, respectively, of the overall average yield. For P0 (average of treatments 0, K, N and NK in Figure 2.1) and P1 (average of treatments P, PK, NP and NPK), these values were 97 and 103%. For K0 (average of treatments 0, P, N and NP in Figure 2.1) and K1 (average of treatments K, PK, NK and NPK) they are 101 and 99%. Despite the variation in relative yields of the various treatments (Figure 2.1), it is obvious that N was by far the most limiting nutrient on this young marine clay soil. Crops responded moderately to P applications, but differences in response were observed between cereals and other crops and between the initial and later years of the experiment (see Section 2.3.7,Table 2.6). No effect of K application on crop yields was found.

### *2.3.3. Yields and responses to N and P per crop and per year*

Observed yields of all crops and years are shown in Table A.2.1 of Appendix 2. For each NP combination, yields were averaged across K0 and K1. Yields varied a lot among the years; the coefficients of variation were between 4 and 16% for the N1-treatments and between 19 and 36% for the N0-treatments. The difference in yield variation among the crops as summarized in the coefficients of variation of the average yields (bold numbers), was 14% for the cereals, and 18% for the root and tuber crops (sugar-beets and potatoes).

Also the roots of mean square error (RMSE) and the corresponding coefficients of variation (Italic numbers), so the variation in non-explained yield differences among treatments, were somewhat smaller for the cereals than for the root and tuber crops (Italic/bold numbers).

Average root DM-yields of *sugar-beet* were around 8000 kg ha$^{-1}$ for the fertilizer treatments without N, while adding fertilizer N raised yields to a level of about 14000 kg ha$^{-1}$ (Table A.2.1). Average grain yields of *spring-barley* were around 2900 kg ha$^{-1}$ for the fertilizer treatments without N, and almost 6000 kg ha$^{-1}$ when fertilizer N was applied. After the large winter-rains in 1994, N0 yields were lower than in the other years and (N1-N0), the average response to N, was greater. Average tuber DM yields of *potatoes* were around 7500 and 13000 kg ha$^{-1}$, respectively, for the N0 and N1 treatments. In 1995, all potato yields but especially the N0 yields were much lower than in the other years (Table A.2.1) which likely was a consequence of the very high rains in February and March (219 in 1995 versus 92 mm in the other years).

**Table 2.2**
Soil extractable P and K at the start of the experiment (1975) and eight years later; corresponding P and K fertilizer recommendations (Van Dijk & Van Geel, 2010). Soil analytical data and fertilizer applications are in the units used in the Netherlands.

| Year | Treatment | | Potatoes | Sugar-beets | Barley | Wheat |
|---|---|---|---|---|---|---|
| | | P-water mg $P_2O_5$ per litre | Recommended $P_2O_5$, kg/ha | | | |
| 1975 | At start | 26 | 135 | 95 | 45 | 0 |
| 1983 | P applied | 29 | 125 | 80 | 25 | 0 |
| | No P applied | 12 | 180 | 140 | 100 | 50 |
| | | K-HCl mg $K_2O$ per 100 g | Recommended $K_2O$, kg/ha | | | |
| 1975 | At start | 17[a] | 140 | 140 | 70 | 70 |
| 1983 | K applied | 28 | 65 | 65 | 0 | 0 |
| | No K applied | 26 | 75 | 75 | 15 | 15 |

[a] K-HCl must be multiplied by *b* to get the so-called K-number on which the fertilizer K recommendations are based. For the present soil, *b* = 0.954.

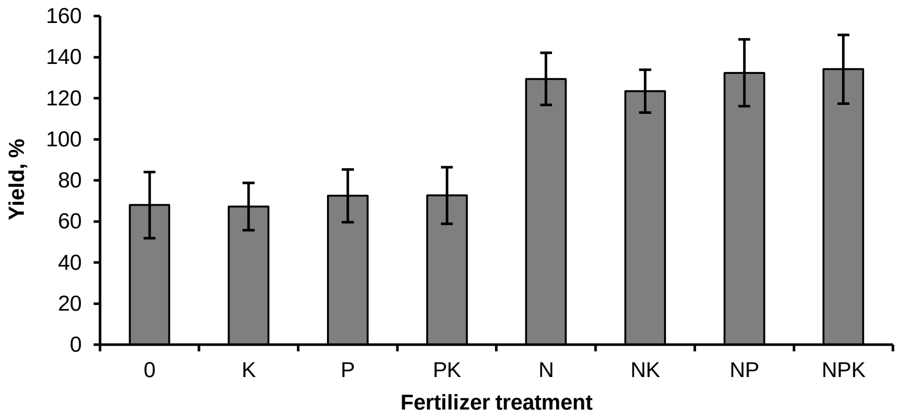


**Fig. 2.1.** Relative yields in relation to fertilizer treatment. In each year, the average yield of the eight fertilizer treatments was set at 100%. Data were averaged across 28 years.

Average grain yields of *winter-wheat* were around 6750 kg ha$^{-1}$ for the fertilizer treatments with N, and around 3675 kg ha$^{-1}$ when no fertilizer N is applied. The relatively large N1-yields of about 8300 kg in 1992 (Table A.2.1) can, at least partly, be ascribed to the larger N application than in the other years (70 versus 57.5 kg ha$^{-1}$).

**Table 2.3**
Winter rainfall (December – April, mm) and fertilizer N application at N1 (kg $ha^{-1}$), mean across years and corresponding standard deviation.

| Crops | | | | | | | | Mean | St dev |
|---|---|---|---|---|---|---|---|---|---|
| Sugar-beets | Year | 1975 | 1979 | 1984 | 1988 | 1993 | 1999 | | |
| | Rain | 369 | 364 | 315 | 406 | 270 | 349 | 345 | 47 |
| | N1 | 150 | 150 | 150 | 150 | 150 | 150 | 150 | 0 |
| Spring-barley [a] | Year | 1976 | 1985 | 1989 | 1994 | 1998 | 2000 | | |
| | Rain | 182 | 218 | 249 | 418 | 347 | 410 | 304 | 101 |
| | N1 | 57.5 | 57.5 | 57.5 | 80 | 60 | 80 | 65 | 11 |
| Potatoes | Year | 1977 | 1982 | 1986 | 1991 | 1995 | 2001 | | |
| | Rain | 315 | 246 | 283 | 199 | 478 | 378 | 316 | 91 |
| | N1 | 108 | 210 | 210 | 180 | 240 | 210 | 193 | 46 |
| Winter-wheat | Year | 1978 | 1983 | 1987 | 1992 | | | | |
| | Rain | 216 | 396 | 281 | 246 | | | 285 | 79 |
| | N1 | 57.5 | 60 | 40 | 70 | | | 57 | 12 |
| Other crops | Year | 1981[b] | 1990[c] | 2002[c] | 1996[d] | 1997[d] | | | |
| | Rain | 349 | 306 | 370 | 109 | 181 | | 263[e] | 113[f] |
| | N1 | 15.5 | 57.5 | 180 | 108 | 203 | | | |

[a] Also in 1980 spring-barley was grown, but this year was not included in further data elaboration because of exceptional weather conditions (see text). Winter rain was 322 in 1980.
[b] Flax, seeds [c] Spring-wheat, grains, 15% moisture [d] Silage maize, total DM
[e] Mean rainfall in 1981, 1990, 1996, 1997, 2002
[f] Standard deviation of rainfall in 1981, 1990, 1996, 1997, 2002

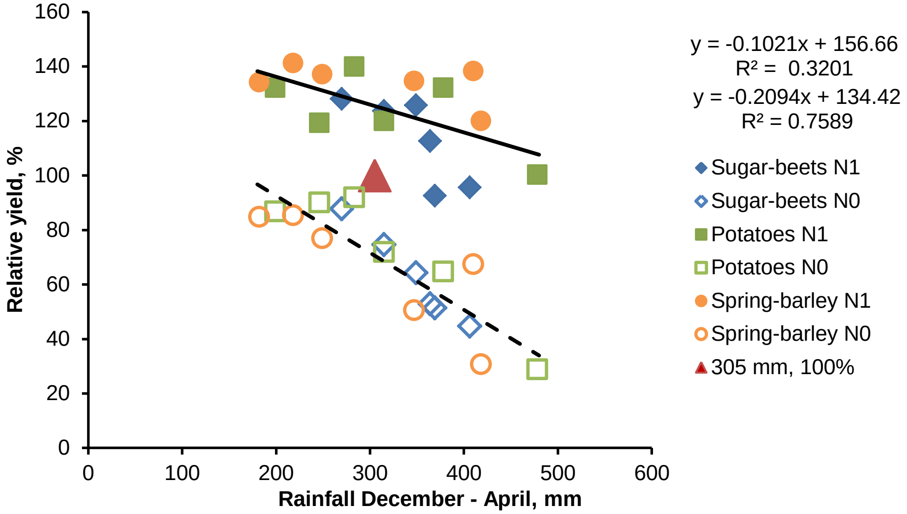


**Fig. 2.2.** Relations between relative measured yields and rainfall in the preceding months of December up to and including April. For each crop, yields adjusted to 305 mm rainfall, and averaged across all fertilizer treatments were set at 100%. Points refer to averages across P1K1, P1K0, P0K1and P0K0 per crop, either at N1 or N0. Regression equations were calculated at N1 and N0 for the points of the three crops together. Sugar-beets: root dry-matter yields. Spring-barley: grain yield, 15% moisture. Potatoes: tuber dry-matter yields.

Table A.2.1 also presents the yields of *flax*, *spring-wheat*, and *silage maize*, again averaged across K0 and K1. These crops were grown in the years when it was impossible to plant the intended crop (see Section 2.2.1). The picture is similar to that of the four main crops: clear-cut response to N and an irregular pattern of response to P, only for spring-wheat significant.
Maize had the relatively biggest RMSEs and coefficients of variation (CV) of all crop/year combinations, likely because it was more difficult to get representative yield data of maize than of other crops from such small areas.

*2.3.4. Yields in relation to winter rains and other weather conditions*

The variation in crop yields among the years proved related to the variation in precipitation in the preceding winters. Rain data and N rates at N1 are presented in Table 2.3. Figure A.2.1 of Appendix 2 shows the relationships between observed yields and winter rains for sugar-beets, spring-barley and potatoes, the crops with at least six harvests. N0 yields were more closely related to winter rains than N1 yields. The relation between *spring-barley* yields and winter rainfall was non-existent for N1P1, while significant for yields of the other three treatment combinations (Figure A.2.1). Year 1980 (Year 6 of the experiment) was left out of consideration in Figure A.2.1 because of unusual and poor weather conditions: too high rainfall in July (139 vs 66 mm), low temperature in May-July (14.4 vs 15.9 $^{o}$C) and low radiation in June and July (1466 vs 1772 J $cm^{-2}$ $day^{-1}$). As a result, the 1980 yields, especially those of N1, were outliers in the relations between yield and winter rainfall.

Following the procedure described in Section 2.2.5, the yields of sugar-beets, potatoes and spring-barley were adjusted to a winter rainfall of 305 mm, being the rainfall from December to April averaged across the years 1975 to 2002, for each of the four NP treatments. A summary of the relations is shown in Figure 2.2. Relative yields, adjusted to 305 mm rainfall, of sugar-beets, spring-barley, and potatoes, were averaged across all eight fertilizer treatments and set at 100%. Especially at N0, the points of the three crops fit well to the common regression line. The slope of the N0 line is twice that of the N1 line. As a consequence the response to N of adjusted yields was larger or smaller than that of measured yields in the years with more and less than 305 mm winter-rains, respectively.

Coefficients of variation (CV) of the adjusted average yields (Table 2.4) were 5.6, 8.9 and 8.9%. They are considerably smaller than the CVs of the observed yields (Appendix 2, Table A.2.1) which were 17.4, 14.0 and 18.3%. The reduction in CV, brought about by the adjustment to 305 mm winter rains, was much stronger for N0 than for N1 treatments. The responses to N, expressed as N1-N0 in Table 2.4, were five to nine times as strong as the responses to P (= P1 – P0), but the

coefficient of variation (CV) was for the response to P five to seven times as high as the CV for the response to N. The adjustment to 305 mm winter rains reduced the coefficient of variation (CV) for the responses to N stronger than for the responses to P.
It was tried to relate the variation in winter rains adjusted yields to other weather characteristics such as temperature and radiation. No consistent connections were found.

Although it was not realistic to try to establish quantitative relationships between yields and winter rains for the crops with less than six harvests, there were indications that winter rains negatively affected yields. Spring-wheat yields at N0 were around 2100 in 2002 and 4200 in 1990 (Appendix 2, Table A.2.1) corresponding with winter-rains of 370 mm in 2002 and 306 mm in 1990. At N1, however, yields were around 7600 and 6700, which likely is caused by the greater recommended N application in 2002 (180 kg ha-1) than in 1990 where it was 57.5 kg ha-1 (Table 2.3). A similar picture was obtained with silage maize. In 1997, winter rain was 181 mm and N0 yield around 6500, and in 1996 rain was 109 mm and N0 yield around 7400 kg $ha^{-1}$. Even N1 yields were higher in 1996 (around 11300 kg $ha^{-1}$) than in 1997 (around 9800 kg $ha^{-1}$), although N application was less in 1996 (108 versus 203 kg $ha^{-1}$; Table 2.3).

Winter-wheat yields were more clearly related to rainfall in December and January than to rainfall from December to April (not shown). This pointed to a strong direct negative effect of water-logging to this winter crop rather than to an indirect effect caused by leaching or denitrification of soil N. Average rainfall in December and January (not shown) was 158 mm in the wet years of 1983 and 1987 with average yields around 4800 kg $ha^{-1}$ (Appendix 2, Table A.2.1), while it was 101 mm with average yields around 6000 kg $ha^{-1}$ in the other two winter-wheat years.
In general, N1 yields were less closely related to winter rainfall than N0 yields because the recommended N applications were higher in the years with much winter precipitation, thus partly compensating for soil N losses caused by winter rains. It is also possible that the applied N stimulated root growth and by that, the uptake of soil N that had moved to greater depth (see also Chapter 3, Section 3.3.2.).

### *2.3.5. N input (INMAX) for maximum yield (YMAX) and its relationship to winter rains*

From 1994 to 2002, N was applied at three levels: 0, 67 and 133% of the recommended rate (N1) as based on soil mineral N. Figure 2.3 shows the nine response curves for the five different crops grown in between 1994 and 2002. These curves represent the mean observed yields of the four treatments P1K1,

**Table 2.4**
Yields and responses to N (= N1 – N0) and to P (= P1 – P0) per year, adjusted to 305 mm winter rainfall from December to April. Adjustments were made per NP combination via regression equations of Figure A.2.1 in Appendix 2. Right-hand columns: means per treatment across years and corresponding standard deviations (St dev) and coefficients of variation (CV). Significance (p) see Table A.2.1

| **Crop** | **Calendar years, years since start of experiment** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Sugar-beets, root DM** | 1975<br>1 | 1979<br>5 | 1984<br>10 | 1988<br>14 | 1993<br>19 | 1999<br>25 | **Mean** | **St dev** | **CV** |
| N1P1 | 14282 | 16626 | 16078 | 17026 | 16504 | 18198 | 16452 | 1285 | 7.8 |
| N1P0 | 13200 | 15557 | 15619 | 13690 | 13317 | 16298 | 14613 | 1362 | 9.3 |
| N0P1 | 8843 | 9278 | 9597 | 10252 | 9836 | 10380 | 9698 | 584 | 6.0 |
| N0P0 | 9502 | 9019 | 9984 | 9549 | 9209 | 9500 | 9460 | 330 | 3.5 |
| Average | 11457 | 12620 | 12820 | 12629 | 12216 | 13594 | 12556 | 704 | **5.6** |
| N1-N0 | 4569 | 6943 | 6058 | 5457 | 5388 | 7308 | 5954 | 1030 | 17.3 |
| P1-P0 | 212 | 664 | 36 | 2019 | 1907 | 1390 | 1038 | 856 | 82.5 |
| **Spring-barley, grains 15%** | 1976<br>2 | 1985<br>11 | 1989<br>15 | 1994<br>20 | 1998<br>24 | 2000<br>26 | **Mean** | **St dev** | **CV** |
| N1P1 | 6012 | 6263 | 6308 | 5782 | 6111 | 6576 | 6175 | 272 | 4.4 |
| N1P0 | 5487 | 5973 | 5675 | 5244 | 5975 | 6044 | 5733 | 321 | 5.6 |
| N0P1 | 2802 | 3137 | 3334 | 2243 | 2521 | 4063 | 3017 | 648 | 21.5 |
| N0P0 | 2794 | 3072 | 2610 | 2259 | 2623 | 3568 | 2821 | 452 | 16.0 |
| Average | 4274 | 4611 | 4482 | 3882 | 4308 | 5063 | 4436 | 394 | **8.9** |
| N1-N0 | 2952 | 3013 | 3020 | 3262 | 3471 | 2494 | 3035 | 329 | 10.8 |
| P1-P0 | 267 | 177 | 678 | 261 | 17 | 513 | 319 | 238 | 74.7 |
| **Potatoes, tuber DM** | 1977<br>3 | 1982<br>8 | 1986<br>12 | 1991<br>17 | 1995<br>21 | 2001<br>27 | **Mean** | **St dev** | **CV** |
| N1P1 | 12407 | 12308 | 15513 | 13327 | 12841 | 14619 | 13503 | 1295 | 9.6 |
| N1P0 | 12869 | 11525 | 13329 | 12308 | 11392 | 14394 | 12636 | 1141 | 9.0 |
| N0P1 | 7700 | 8529 | 9877 | 6918 | 7428 | 9072 | 8254 | 1110 | 13.4 |
| N0P0 | 7802 | 7543 | 8317 | 6294 | 6677 | 7866 | 7417 | 773 | 10.4 |
| Average | 10195 | 9976 | 11759 | 9712 | 9584 | 11488 | 10452 | 935 | **8.9** |
| N1-N0 | 4887 | 3881 | 5324 | 6212 | 5064 | 6037 | 5234 | 847 | 16.2 |
| P1-P0 | -282 | 884 | 1872 | 822 | 1100 | 716 | 852 | 694 | 81.5 |

P1K0, P0K1, and P0K0. Using the regression coefficients of the relations between yields and N application (Table 2.5), the required input of N (INMAX) for maximum yield (YMAX), was calculated (INMAX = -*b/2a*). In the curves of Figure 2.3, the points of YMAX are indicated by open triangles. The corresponding N rates are INMAX. Because the value of *'a'* was negative in all years and for all crops, INMAX had realistic values, and they were within the range of the experimental N applications. Except for silage maize, INMAX (Table 2.5) was larger than N1 (Table 2.3) that was based on soil mineral N analyses. The yields obtained at N1 were on average 98.5% of the maximum yield (YMAX), while N1 was on average 88% of INMAX, so the relative differences in yields were considerably smaller than the relative differences in N application reflecting that YMAX is situated in the almost flat part of the response curves (Figure 2.3).

Figure 2.4 shows INMAX in relation to rainfall from December up to and including April. INMAX increased with increasing winter rainfall, as illustrated by the crops with two (potatoes, silage maize) or three (spring-barley) yields between 1994 and 2002. The points for sugar-beets, silage maize, potatoes and spring-wheat were situated around a same line, which was less steep than the line for spring-barley. At a winter rainfall of 305 mm, INMAX for spring-barley (found by extrapolation) is around 40 kg $ha^{-1}$, 160 kg $ha^{-1}$ less than INMAX for the other crops (around 200 kg $ha^{-1}$). The slopes of the regression lines show that per 100 mm increase in winter rainfall an additional application of about 63 kg N $ha^{-1}$ was required to reach maximum yield of spring-barley and about 43 kg $ha^{-1}$ for the other crops.

### *2.3.6. N recommendation as based on winter rains*

In Table 2.5, the equation parameters of the lines in Figure 2.3 are presented, and derived INMAX and YMAX. Using equations from Figure 2.4, INWR (standing for input of N (IN, kg $ha^{-1}$) in relation to winter rains (WR, mm) was calculated as a function of rainfall from December to April. The somewhat simplified equations were INWR = 0.43 · WR + 70 for sugar-beets, potatoes, spring-wheat and silage-maize, and INWR = 0.63 · WR – 150 for spring-barley. The values of INWR were sometimes larger, sometimes smaller than INMAX but on average INWR and INMAX were (of course) equal, and both were larger than N1. On average, INWR is about 12% larger than N1, the recommended N rate based on soil mineral N.

The average yields (YINWR) corresponding to INWR are, however, not more than half a percent larger than the yields corresponding to N1 (Figure 2.5), again reflecting that YMAX and hence also YINWR, were situated in the almost flat part of the response curves in Figure 2.3.

**Table 2.5**
Crops, harvest year, rainfall from December to April (mm), values of the parameters of the equations $y = a \cdot x^2 + b \cdot x + c$ of regression lines in Figure 2.3, input rates of N required for maximum yield (INMAX = $-b/2a$) and corresponding maximum yields (YMAX).

| Crop | Year | Rain | *-a* | *b* | *c* | INMAX | YMAX |
|---|---|---|---|---|---|---|---|
| Sugar-beets | 1999 | 349 | 0.2410 | 87.574 | 8071.7 | 182 | 16027 |
| Silage maize | 1996 | 109 | 0.4471 | 84.053 | 7465.9 | 94 | 11416 |
| | 1997 | 181 | 0.1273 | 48.053 | 6513.7 | 189 | 11048 |
| Potatoes | 2001 | 378 | 0.1164 | 58.035 | 6766.1 | 249 | 14000 |
| | 1995 | 478 | 0.1007 | 56.707 | 3017.0 | 282 | 11000 |
| Spring-wheat | 2002 | 370 | 0.1167 | 51.847 | 2082.3 | 222 | 7841 |
| Spring-barley | 2000 | 410 | 0.3682 | 75.818 | 2991.2 | 103 | 6894 |
| | 1998 | 347 | 0.8422 | 113.280 | 2242.5 | 67 | 6052 |
| | 1994 | 418 | 0.3380 | 77.477 | 1363.7 | 123 | 5804 |

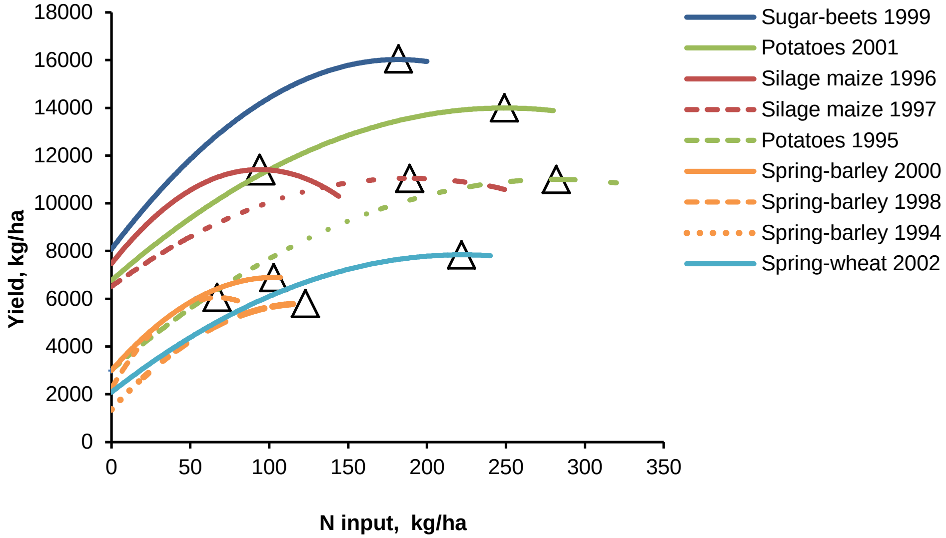


**Fig. 2.3.** Yields (averaged across P1K1, P1K0, P0K1, P0K0) in relation to N input. Maximum yields (YMAX), obtained at INMAX, are indicated by open triangles. See Section 2.3.5 and Table 2.5.

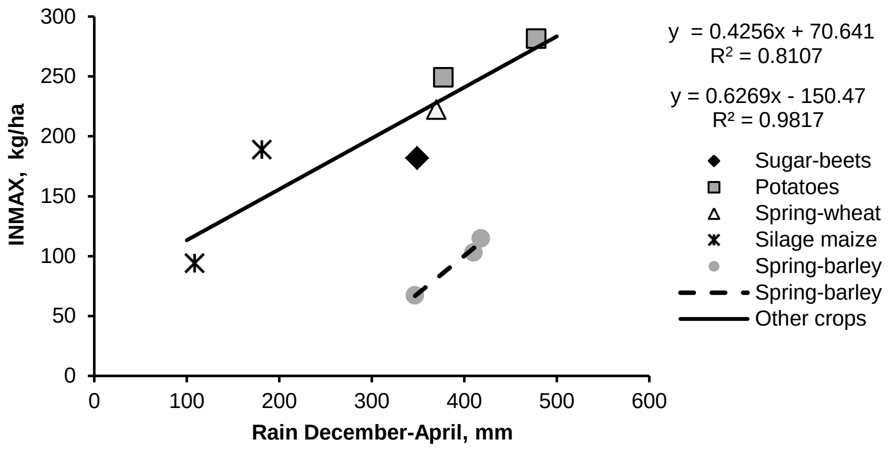


**Fig. 2.4.** N input rate (INMAX) required for maximum yield in relation to winter rainfall (December-April). See Section 2.3.5.

### *2.3.7. Evolution of yields and yield responses to N and P during the long-term experiment*

To verify whether the responses to nutrient application steadily increased because the soil in the non-fertilized control plots gradually became poorer, yields were plotted versus time since the start of the long-term experiment. Yields adjusted to 305 mm winter rain were used to minimize variation among years caused by differences in winter rainfall. Two examples are given in Figure 2.6. The left-hand graph shows the evolution of sugar-beet root DM yields at P1 and P0 and of their differences representing the response to P. The right-hand graph shows the evolution of potatoes tuber DM yields at N1 and N0 and of the response to N. The response to P by sugar-beets increased indeed over time (by 67 kg $ha^{-1}$ $y^{-1}$, Table 2.6) but this was not related to decreasing P0 yields but to increasing P1 yields. The latter probably is connected to the varieties grown, being Monohil in Years 1 and 5, Regina in Years 9 and 13, and unknown in Years 19 and 25.

The right-hand graph of Figure 2.6 shows a practically horizontal line for potato yields at N0. Its slope was slightly negative but the accompanying $R^2$ was far too small to take this decrease seriously. Nevertheless, the negative slope contributed to the increase of the response to N by potatoes (N1 – N0). The negative slope at N0 was related to the very low measured N0 potato yields in Year 21 (= 1995) caused by the extremely high winter rainfall of 478 mm (Table 2.3); the points at 478 mm winter rain were all situated below the regression lines of potatoes in Figure A.2.1 (Appendix 2), suggesting that the adjustment for winter rains was insufficient for the yields of the year with that rainfall.

The hypothesized decreases in yields did neither show up for sugar-beets at N0, nor for potatoes at P0 or for spring-barley at N0 and P0 (Table 2.6). It points to a stable soil fertility. In the case of sugar-beets, N0 yields even significantly

**Table 2.6**
Slopes (*b*), intercepts (*c*) and $R^2$s of linear equations ($y = b \cdot x + c$) relating yields and yield responses to year since the start of the long-term experiment. Yields are adjusted to 305 mm winter rain. Data at N1 are averages of N1P1 and N1P0, and data at N0 are averages of N0P1 and N0P0. Similarly, data at P1 are averages of N1P1 and N0P1, and data at P0 are averages of N1P0 and N0P0.

| Crop | Nutrient level | Nitrogen | | | Phosphorus | | |
|---|---|---|---|---|---|---|---|
| | | *b* | *c* | $R^2$ | *b* | *c* | $R^2$ |
| Sugar-beets | 1 | 82.87 | 14511 | 0.3888 | 89.91 | 11966 | 0.7684 |
| | 0 | 30.36 | 9205 | 0.5761 | 23.32 | 11749 | 0.0816 |
| | 1 - 0 | 52.51 | 5306 | 0.2053 | 66.60 | 217 | 0.4781 |
| Spring-barley | 1 | 11.23 | 5771 | 0.1268 | 11.36 | 4410 | 0.0499 |
| | 0 | 10.56 | 2746 | 0.0315 | 10.43 | 4107 | 0.0668 |
| | 1 - 0 | 0.67 | 3024 | 0.0003 | 0.93 | 304 | 0.0012 |
| Potatoes | 1 | 52.46 | 12300 | 0.1662 | 34.52 | 10372 | 0.0734 |
| | 0 | -9.67 | 7977 | 0.0087 | 8.27 | 9905 | 0.0071 |
| | 1 - 0 | 62.13 | 4323 | 0.4140 | 26.25 | 467 | 0.1102 |

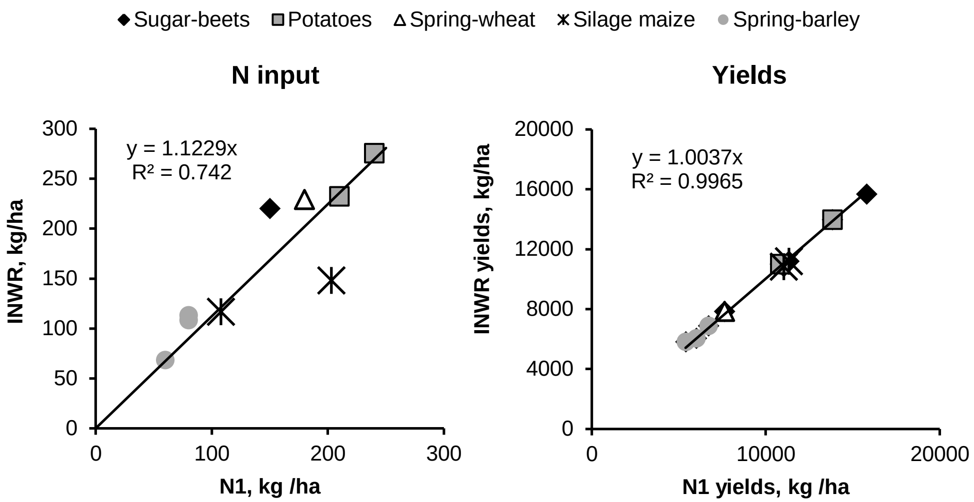


**Fig. 2.5**. Left-hand graph: Comparison of recommended N input rates as based on winter-rains (INWR) with recommended N rates as based on soil mineral N (N1). Right-hand graph: comparison of calculated yields based on INWR recommendations with calculated yields based on N1 recommendations.

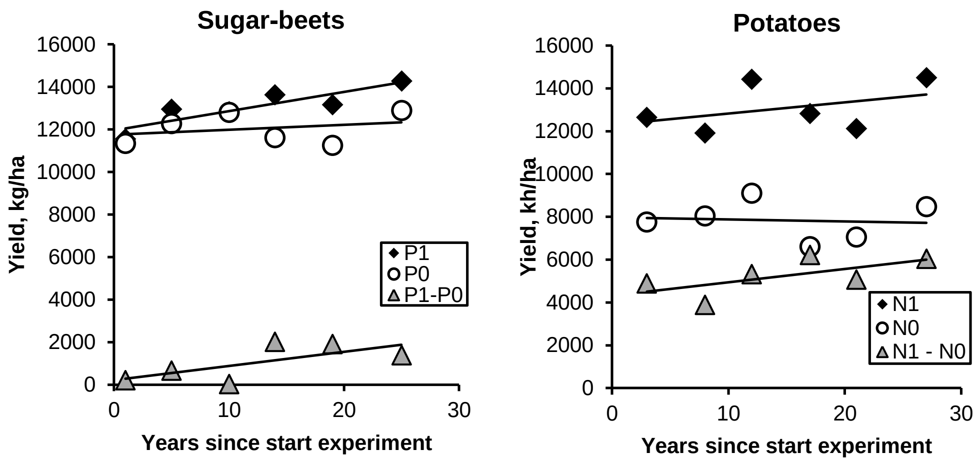


**Fig. 2.6**. Left-hand graph: evolution of P1 and P0 sugar-beet root dry-matter yields adjusted to 305 mm winter rain, and of the response to P. Right-hand graph: evolution of N1 and N0 potatoes tuber dry-matter yields adjusted to 305 mm winter rain, and of the response to N. Each point at N1 is the average of the yields at N1P1 and N1P0, and each point at N0 is the average of the yields at N0P1 and N0P0. Each point at P1 is the average of the yields at N1P1 and N0P1, and each point at P0 is the average of the yields at N1P0 and N0P0.

increased, by 30 kg $ha^{-1}$ $y^{-1}$ (Table 2.6), being the middle of the increase of N0P1 with 60 kg ha-1 $y^{-1}$ ($p = 0.011$) and N0P0 with 2 kg $ha^{-1}$ $y^{-1}$ (not shown). The responses to N by spring-barley did not change, the average response was 3035 (Table 2.4), very close to 3024 the value of parameter c in Table 2.6.

In conclusion, the small values of the slopes (*b*) and of $R^2$ (Table 2.6) indicate that yields and yield responses hardly changed during the 28 years of the experiment, the least so for spring-barley. Where changes over time were observed they were in positive direction, most likely resulting from of improved crop varieties with greater potential yields and better nutrient use efficiency. Table 2.6 once more demonstrates that the treatment sequence of yields remained the same for all crops from the beginning to the end of the experiment: N1 > P1 > P0 > N0. Hence, the response to N was always greater than the response to P. Also the values of parameter *c* of Nutrient level (1 – 0) in Table 2.6 were evidence that the response to N was always greater than the response to P.

### *2.3.8. Evolution of the differences between maximum and control yields during the long-term experiment*

Considering rain-adjusted N1P1 yields as the maximum yields that could be obtained with the used standard N and P inputs, the maximum yields of sugar-beets and potatoes significantly increased over time, by 120 and 64 kg $ha^{-1}$ $y^{-1}$, respectively (Figure 2.7, top). Potato yields were calculated to increase by 82 kg $ha^{-1}$ $y^{-1}$, when experimental Year 12 was not included in the regression equation. There was no explanation for the exceptionally large yield in Year 12. Spring-barley yields changed too little in the experimental period between 1975 and 2002 to be significant (Figure 2.7). The increase of the N1P1 yields of sugar-beets and potatoes were ascribed to improved varieties of sugar-beets and potatoes. This did not happen with spring-barley, likely because not sufficient N was applied at N1 as argued in Chapter 4.

The control yields (N0P0) did not significantly change during the experiments (Figure 2.7, middle). It is noted that the N0P0 yields of potatoes in Figure 2.7 decreased somewhat stronger than the N0 yields in Figure 2.6, pointing to a weak positive effect by P on potato yield (see also Table A.2.1 and Table 2.4). Yield differences (Δyield, bottom Figure 2.7) of sugar-beets and potatoes increased, while those of spring-barley remained at the same level.
The three graphs of Figure 2.7 represent a summary of this 28 years long-term experiment showing sustainable fertility of this former sea bottom, as well as successful crop improvement of sugar-beets and potatoes in the Netherlands.

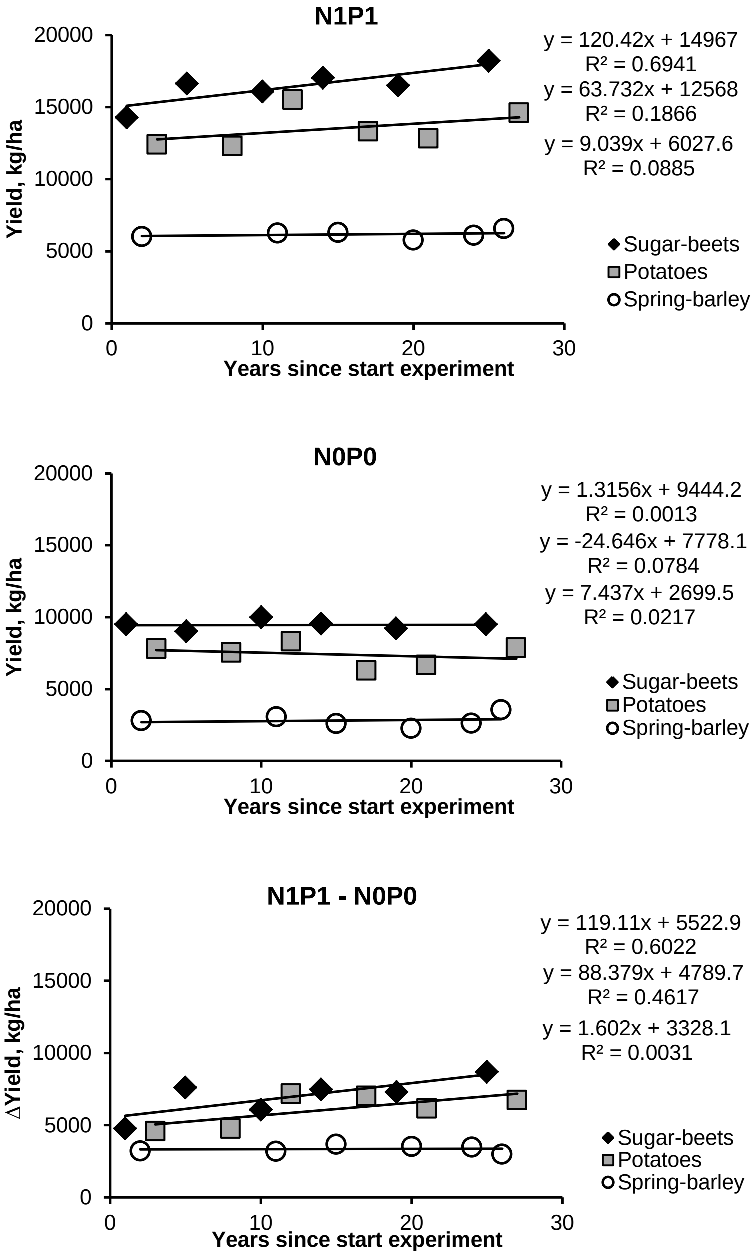


**Fig. 2.7.** Evolution of N1P1, N0P0 and ∆yields (N1P1- N0P0), adjusted to 305 mm winter rains, of sugar-beets, potatoes, and spring-barley. When Year 12 of potatoes is not included in the N1P1 regression line, the equation changes into $y = 82.25x + 11850$ with $R^2 = 0.7211$, and when Year 12 of potatoes is not included in the (N1P1 – N0P0) regression line the equation changes into $y = 99.806x + 4347$ with $R^2 = 0.7446$

## 2.4. Discussion

### *2.4.1. Main findings*

This chapter reported on the annual yield responses to various N, P and K dressings during a 28-years long-term field trial. The basic hypothesis at the start of the study was that the need for nutrient input would gradually increase because the former sea-bottom soil would progressively become depleted of the nutrients that were not applied. It was unknown how long it would take before depletion would manifest itself, and whether different crops would behave differently in showing up responses to N, P and K applications.

The major outcomes of the 28-years research were that without N input crop yielded only 40 to 60% of the yields obtained with N application (Figure 2.1). This difference was evident from the beginning of the long-term trial. Effects of P input gradually became more visible, but not for all crops to the same extent, and were seldom statistically significant (Appendix 2, Table A.2.1). Responses to K application were not at all visible, although responses to K could be expected in view of the recommendations mentioned in Table 2.2. It is possible that the used acid extraction solution of 0.1 M HCl was partly neutralized in these soils containing about 10% $CaCO_3$. As a result, crop-available K was underestimated with the standard soil analysis, and K application was recommended while no K input was needed. In Chapter 3, it is shown that crops did take up fertilizer K but were unable to efficiently use it for growth. More or less the same holds for P, be it that some extra crop production was possible with the absorbed fertilizer P.

The present study showed that a more detailed understanding of the results in long-term experiments is complicated by various factors contributing to uncontrolled variation in crop performance. Yields differed considerably among the years depending on weather conditions, mainly on winter-rains. No clear effects of solar radiation and temperature were found (Section 2.3.4), perhaps because these weather characteristics varied less among years than rainfall and yields. Like in other long-term experiments (Persson et al., 2008), also in our trial results and conclusions were affected by the introduction of new cultivars with higher yield potential. Moreover, the management of crop residues has not always been the same. Furthermore, heterogeneity among the experimental plots seemed to increase (Appendix 2, Table A.2.1, CV%), which could partly be a result of the experimental treatments themselves, e.g. by build-up of residual fertilizer phosphorus.

### *2.4.2. Influence of winter rains on yields and recommended N application rates*

The influence of winter rains on yield was always stronger at N0 than at N1. The applied N mitigates the differences in soil N. From Cycle 3 onwards, N1 was based on measured soil mineral N and indirectly the differences in winter rains were thus already taken into account. The yield responses to N always were great. The measured responses (N1-N0) showed a coefficient of variation (VC) among the years ranging from 17% for sugar-beets via 23.3% for spring-barley to 28% for potatoes (Appendix 2, Table A.2.1). After adjustment to 305 mm winter rains, the VC of (N1-N0) among years remained 17% for sugar-beets but it was less for spring-barley (11%) and for potatoes (16%) (Table 2.4). The variations in the adjusted response to N could not be related to differences in radiation during the growing season, although their coefficients of variation (11 to 16 %) were in the same order of size. The variation among the years in summer temperature was only around 5% and it was not related to variation in the response to N.

Winter rains seldom were included in studies on weather-yield relationships. It may be considered as a missed opportunity. It is well possible that relationships between observed and simulated yields of sugar-beets could be improved if winter rains were taken into account, *e.g.* in studies such as on the implications of annual variation in weather on optimum nitrogen input (de Koeijer et al., 2003). The importance of preceding rains was also shown in another study at the A.P. Minderhoudhoeve. Even soil organic matter (SOM) was affected by rains in the preceding year; the yearly change in SOM% was positive when rainfall was 600-700 mm, and negative when rainfall was more than 870 mm (Lantinga et al., 2013). Figure 2.5 showed that the N recommendation rates based on the amount of winter-rains (INWR) were about 12% larger than the N recommendation rates based on N mineral analyses (N1), but the corresponding calculated yields were equal for the two methods (Figure 2.5). Therefore it is proposed modify the equations from Figure 2.4 by a factor of about 0.9, resulting in about INWR = 0.38 · WR + 60 for sugar-beets, potatoes, spring-wheat and silage-maize, and INWR = 0.55 · WR – 135 for spring-barley, where INWR stands for N input recommendations (kg $ha^{-1}$) as based on winter rains (WR, mm).

### *2.4.3 Crop response to P*

From Table 2.4 it can be derived that the yield responses to P, relative to the average P0 yield adjusted to 305 mm winter rain, were 7.5% for barley, 8.5% for potatoes and 8.6% for sugar-beets. Their (insignificant) increase over time could not be ascribed to diminishing P0 yields (Table 2.6). Hence, it was impossible to predict at what time the soil would be depleted of P. Like for N, it is credible for P that better crop varieties made better use of soil P and exploited more efficiently the enlarging amount of residual fertilizer P accumulating in the soil.

### *2.4.4 Yield trends*

Although the adjusted yields of sugar-beet increased over time even when no N was applied, the response to N by sugar-beets was increasing as well (Table 2.6). Both, increasing N0 yields and increasing response to N likely must entirely be attributed to an increase in yield potential and nutrient use efficiency of new varieties.

Increasing yields of the same crops as used in this study (sugar-beets, potatoes, spring cereals) were also found in a 60-years long-term experiment in Germany, even when no N was applied (Merbach et al., 2013). Our results largely agree with those of a recent study on genetic progress in yields of sugar-beets, potatoes, and spring-barley in the Netherlands (Rijk et al, 2013). Our experimental period (1975-2002) has a big overlap with the period (1980-2010) considered in their study. Between 1980 and 2002, sugar yield increased on average by 86 kg $ha^{-1}$ $y^{-1}$. Assuming that sugar constitutes 70% of root dry matter, the average root dry matter yield increase was 123 kg $ha^{-1}$ $y^{-1}$, being the same as the 120 kg (Figure 2.7, top) found in our experiment. The increase in dry-matter yields of ware potatoes found in variety trials was 30 kg $ha^{-1}$ $y^{-1}$ (Rijk et al, 2013), so lower than the increase of 64 kg $ha^{-1}$ $y^{-1}$ shown in Figure 2.7. In both studies, however, the very large yield variability among years weakens any statement on yield increase of potatoes.

Unlike in our study, spring-barley yields increased, at a rate of 30 to 90 kg $ha^{-1}$ $y^{-1}$ (Rijk et al, 2013). Part of the difference between the two studies may have been caused by difference in N application rate. In our long-term experiment, it was 65 kg N $ha^{-1}$ $y^{-1}$ on average (Table 2.3), while the (not mentioned) N rate in their study probably was higher. A rate of 65 kg N $ha^{-1}$ $y^{-1}$ was below INMAX (Table 2.5) suggesting that yields were somewhat limited by N. This assumption about N limitation is further underlined by studies in Sweden from 1965 to 2006 (Persson et al, 2008) and in France from 1959 to 1999 (Brancourt-Hulmel et al., 2003). Most likely, however, the used varieties did not have the genetic potential of modern varieties of spring-barley (Chapter 4).

## 2.5. Conclusions

In this 28 years long-term NPK factorial experiment on a former sea-bottom soil, no response to K, strong responses to N, and small but gradually increasing, irregular responses to P were found.
Yields of spring-planted crops (sugar-beets, spring-barley, potatoes) were clearly related to rainfall in preceding winter months, especially when no fertilizer N was

applied. For these crops, input N rates required for maximum yield proved related to rainfall in preceding winter (December – April), and were on average 12% higher than the recommendations based on soil mineral N analysis. The response to fertilizer N, applied at a standard rate, increased over time for sugar-beets and potatoes, but did not change for spring-barley. Sugar-beet was the only crop of which N0 yields increased during the experimental period (N0P1 more than N0P0).

The average response to P was about 8% of P0 yields. Although the response to P became greater during the 28 years experiment, there were no signs of decreasing P0 yields. Hence, it was not yet possible to predict at what time soil P would limit yields.

The responses to N and P likely were positively affected by the introduction of new cultivars with higher yield potential, in the course of the experimental period, especially in the case of sugar-beets.

The native fertility of this young marine loam to clay loam soil seemed unchanged during the 28 years of the study. For N0 yields, winter rainfall was far more important than the length of the period since the start of the experiment. When no fertilizers were applied, no significant yield changes in time were observed; only potato yields decreased a little at N0P0 but not at N0P1.

# Appendix 2.

**Table A.2.1**. Per row: harvest year, winter-rains from December to April (mm), observed yields of the four NP combinations [a], average yields, root of mean square error (RMSE), coefficient of variation (CV, %), response to N (= N1 – N0), and response to P (= P1 – P0) with its corresponding significance probability (p); bottom three rows: means per treatment across years and corresponding standard deviations and coefficients of variation. Yields and yield responses are in kg $ha^{-1}$.

| Year | Rain | N1P1 | N1P0 | N0P1 | N0P0 | Average | RMSE | CV, % | N1-N0 | P1-P0 | Signif. (p) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | *Sugar-beets, root DM* | | | | | |
| 1975 | 369 | 11709 | 11518 | 6206 | 6703 | 9034 | 711 | 7.9 | 5159 | -153 | 0.605 |
| 1979 | 364 | 14254 | 14007 | 6847 | 6439 | 10387 | 772 | 7.4 | 7488 | 328 | 0.313 |
| 1984 | 315 | 15676 | 15356 | 9185 | 9547 | 12441 | 1421 | 11.4 | 6150 | -21 | 0.972 |
| 1988 | 406 | 12965 | 11036 | 6090 | 5133 | 8806 | 1593 | 18.1 | 6389 | 1443 | 0.069 |
| 1993 | 270 | 17911 | 14237 | 11278 | 10739 | 13541 | 1608 | 11.9 | 5066 | 2107 | 0.005 |
| 1999 | 349 | 16429 | 15142 | 8567 | 7576 | 11928 | 1856 | 15.6 | 7714 | 1139 | 0.292 |
| Mean | 345 | 14824 | 13549 | 8029 | 7690 | 11023 | *1327* | ***12.0*** | 6328 | 807 | |
| St dev | 47 | 2294 | 1840 | 2033 | 2090 | 1921 | | | 1119 | 899 | |
| CV, % | 13.7 | 15.5 | 13.6 | 25.3 | 27.2 | **17.4** | | | 17.7 | 111.4 | |
| | | | | | | *Spring-barley, grains, 15% moisture* | | | | | |
| 1976 | 182 | 5945 | 5966 | 3727 | 3799 | 4859 | 237 | 4.9 | 2193 | -47 | 0.633 |
| 1980 | 322 | 4252 | 4337 | 2800 | 2841 | 3558 | 193 | 5.4 | 1474 | -63 | 0.394 |
| 1985 | 218 | 6215 | 6312 | 3792 | 3783 | 5025 | 265 | 5.3 | 2476 | -44 | 0.838 |
| 1989 | 249 | 6277 | 5893 | 3755 | 3068 | 4748 | 471 | 9.9 | 2674 | 536 | 0.012 |
| 1994 | 418 | 5844 | 4802 | 1393 | 1335 | 3343 | 451 | 13.5 | 3959 | 550 | 0.003 |
| 1998 | 347 | 6134 | 5810 | 2205 | 2280 | 4107 | 287 | 7 | 3730 | 125 | 0.162 |
| 2000 | 410 | 6633 | 5634 | 3273 | 2710 | 4562 | 506 | 11.1 | 3142 | 781 | 0.024 |
| Mean[b] | 307 | 6175 | 5736 | 3024 | 2829 | 4441 | *370* | ***8.3*** | 3029 | 317 | |
| St dev[b] | 93 | 278 | 509 | 1001 | 944 | 623 | | | 707 | 351 | |
| CV, %[b] | 30 | 4.5 | 8.9 | 33.1 | 33.4 | **14.0** | | | 23.3 | 110.9 | |

| Year | Rain | N1P1 | N1P0 | N0P1 | N0P0 | Average | RMSE | CV, % | N1-N0 | P1-P0 | Signif. (p) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | *Potatoes, tuber DM* | | | | | |
| 1977 | 315 | 12332 | 12756 | 7481 | 7555 | 10031 | 565 | 5.6 | 5026 | -249 | 0.261 |
| 1982 | 246 | 12750 | 12194 | 9823 | 9001 | 10942 | 1305 | 11.9 | 3060 | 689 | 0.212 |
| 1986 | 283 | 15678 | 13578 | 10360 | 8861 | 12120 | 756 | 6.2 | 5018 | 1799 | 0.000 |
| 1991 | 199 | 14122 | 13510 | 9243 | 8914 | 11447 | 603 | 5.3 | 4738 | 471 | 0.072 |
| 1995 | 478 | 11544 | 9430 | 3633 | 2401 | 6752 | 711 | 10.5 | 7470 | 1674 | 0.000 |
| 2001 | 378 | 14072 | 13566 | 7471 | 6062 | 10293 | 1214 | 11.8 | 7053 | 957 | 0.249 |
| Mean | 317 | 13417 | 12506 | 8002 | 7132 | 10264 | *859* | ***8.4*** | 5394 | 890 | |
| St dev | 100 | 1495 | 1607 | 2452 | 2583 | 1881 | | | 1484 | 702 | |
| CV, % | 32 | 11.1 | 12.8 | 30.6 | 36.2 | **18.3** | | | 27.5 | 78.9 | |
| | | | | | | *Winter-wheat, grains, 15% moisture* | | | | | |
| 1978 | 216 | 7565 | 7509 | 4528 | 4741 | 6086 | 283 | 4.6 | 2903 | -79 | 0.503 |
| 1983 | 396 | 6289 | 6530 | 3253 | 3260 | 4833 | 327 | 6.8 | 3153 | -124 | 0.364 |
| 1987 | 281 | 6182 | 6397 | 3375 | 3242 | 4799 | 272 | 5.7 | 2981 | -41 | 0.717 |
| 1992 | 246 | 8277 | 8382 | 3542 | 3462 | 5915 | 427 | 7.2 | 4828 | -13 | 0.944 |
| Mean[c] | 285 | 6679 | 6812 | 3719 | 3748 | 5239 | *294* | ***5.6*** | 3012 | -81 | |
| St dev[c] | 79 | 769 | 607 | 704 | 860 | 733 | | | 128 | 42 | |
| CV, %[c] | 28 | 11.5 | 8.9 | 18.9 | 23 | **14.0** | | | 4.2 | -51.1 | |
| | | | | | | *Other crops* | | | | | |
| 1981[d] | 349 | 924 | 967 | 659 | 730 | 820 | 118 | 14.4 | 251 | -57 | 0.257 |
| 1990[e] | 306 | 6858 | 6597 | 4363 | 4055 | 5468 | 266 | 4.9 | 2519 | 285 | 0.017 |
| 2002[e] | 370 | 7824 | 7447 | 2155 | 2010 | 4859 | 384 | 7.9 | 5553 | 261 | 0.074 |
| 1996[f] | 109 | 11355 | 11302 | 8503 | 6429 | 9397 | 2713 | 28.9 | 3863 | 1064 | 0.314 |
| 1997[f] | 181 | 9579 | 10120 | 7278 | 5750 | 8181 | 2019 | 24.7 | 3336 | 494 | 0.173 |

[a] Yields were averaged across K0 and K1.
[b] Year 1980 was not included in these calculations, because of unusual and poor weather conditions. See text 2.3.4.
[c] Exclusive Year 1992, because N application at N1 in this year was higher than that in the other years
[d] Flax, seeds
[e] Spring-wheat, grains, 15% moisture
[f] Silage maize, total DM

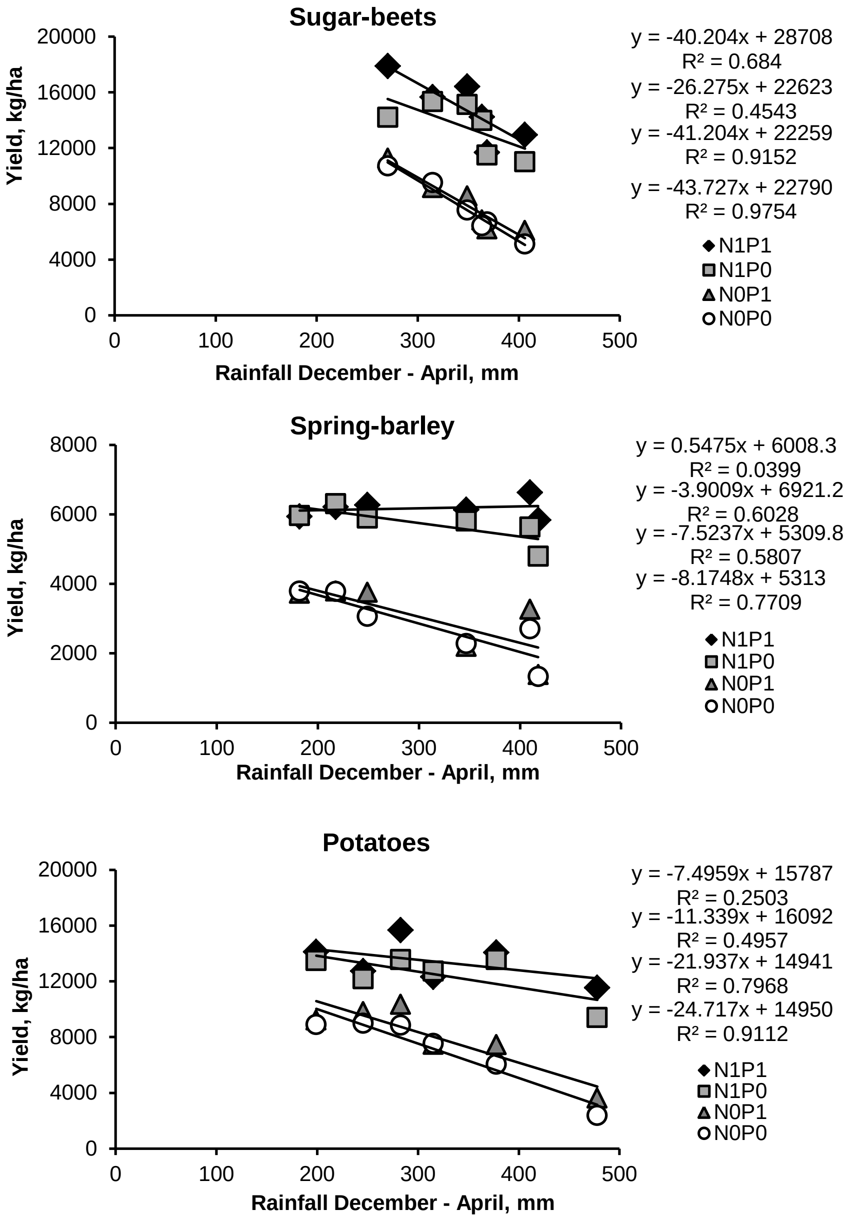


**Fig. A.2.1.** Relations between observed yields and rainfall in the preceding months from December up to and including April. Points refer to averages across K0 and K1; see Section 2.3.4. Equations are in the same order from top to bottom as legend. Sugar-beets: root dry-matter yields. Spring-barley: grain yield, 15% moisture. Potatoes: tuber dry-matter yields.

# Chapter 3

# Availability, uptake and uptake efficiency of N, P and K


## Abstract

The main objectives of this chapter were to get a better understanding of why in a 28 years field experiment (1975 through 2002) at the experimental farm of Wageningen University in the polder Oostelijk Flevoland, crops showed no yield responses to K, highly significant responses to N, and irregular responses to P. This chapter is restricted to six years (1994-1999), in which crops were analysed for N, P and K. The observed nutrient uptakes confirmed this polder soil was poor in N, very rich in K and rich in P. Nutrient availability in soil and input was estimated as the maximum uptake of that nutrient when it was the dominant growth-limiting factor. The amounts of available N, P and K in the soil were 25-80, 23-30 and 110-450 kg $ha^{-1}$ and depended on crop type. The fractions of available N in applied N were more than 90%, except in years after high winter rains. Calculated optimum N rates for maximum N uptake often were beyond the actual rates applied in the trial. Application of P increased the uptake of N a little, especially in the case of potatoes, while K had no effect on the uptake of N. Although P and K inputs hardly influenced yields, they clearly stimulated uptakes of P and K, resulting in luxury consumption of these nutrients. Estimated available fractions of fertilizer P were 25% for spring-barley, 24% for sugar-beets and 6% for potatoes. Estimated available fractions of fertilizer K were around 100% for sugar-beets and potatoes and varied strongly for spring-barley. When no N was applied, 30-50% of available P was taken up and 15-35% of available K, but when N was applied these fractions were 75-100% and 65-100%. The extremely great availability fractions of fertilizer N and K were ascribed to upward movement of sub-soil moisture with easily dissolving nutrients during the growth season. Uptake efficiency was always very high for N. When no N was applied, large fractions of available soil P and K were not taken up by the crops and remained unused. The crop recovery of input P consisted of a direct effect and an indirect effect via stimulated uptake of N.


## Highlights

- Quantities of soil available N, P and K depended on crop type. They were estimated at 25 to 80, 23 to 30, and 110 to 450 kg $ha^{-1}$, respectively.

- After wet winters, fertilizer N had a priming effect on the uptake of soil N.
- Availability fractions in fertilizers were around 90 to 100% for N and K, and varied for P from 6% (potatoes) to 30% (spring-barley).
- Between 55 and 100% of estimated available N was taken up.
- Uptake of P was 30 to 50% of estimated available P when no N was applied and 75 to 100% when N was applied.
- Uptake of K was 15 to 35% of estimated available K when no N was applied and 65 to 100% when N was applied.

**Key words**: available nutrients, factorial NPK, long-term experiment, optimum N rate, soil nutrient depletion, uptake efficiency

## 3.1. Introduction

In 1974, the former department of ‘Agricultural Chemistry’ of the Wageningen University initiated plans for a long-term study of changes in nutrient supply to crops on a former sea bottom. The basic questions were how long it would take before crop performance suffered from shortages in N, P and K, and whether different crops behaved the same and responded similarly to applied nutrients. The experiment was carried out at the ‘A.P. Minderhoudhoeve’ (APM), an experimental farm near Swifterbant in the polder of Oostelijk (Eastern) Flevoland.

Chapter 2 reported on the yields during the long-term experiment running from 1975 through 2002, comprising 28 cropping seasons. The experimental design was a $2^3$ NPK factorial before 1994, and a 3 N $\cdot$ $2^2$ PK factorial since 1994. The research questions were simple and so were the answers. No response to K was found, a highly significant response to N, and irregular responses to P for sugar-beets, potatoes and spring-barley, but never for silage maize and winter-wheat. Yields proved strongly related to rainfall in the preceding winter months, especially when no N was applied. Yields on unfertilized soil, adjusted to average winter rainfall of 305 mm, did not significantly change during the 28 years period.

The main objectives of the study in this chapter were (i) to estimate the supplies of available N, P and K in the soil; (ii) to estimate the fraction of available N, P and K in the applied fertilizers; (iii) to measure the uptake efficiency of available N, P and K; (iv) and thus to better understand crop performance and yield responses to fertilizers as described in Chapter 2.

This chapter deals with the period (1994-1999) in which crops were chemically analysed allowing the measurement of nutrient uptake. It starts presenting yields in relation to the experimental fertilizer treatments. The next subsection is on the uptake of nitrogen (UN) and the influences of P and K inputs on UN. Subsequently UP, the uptake of P, is considered in relation to UN and to P input. The crop recovery of input P (IP) is dissected into an indirect effect via UN and a direct effect of IP. It is followed by a same procedure for UN-UK relationships.

## 3.2. Materials and methods

### *3.2.1. Soil, experimental layout and crop sampling*

Some chemical soil data of the experimental site were given in Chapter 2 (Table 2.2). The soils were classified as calcareous Entisols with a texture of loam to clay loam (25-35% clay), and evaluated as very fertile and very suitable for arable crops (Eilander et al., 1990). In the period from 1994 to 1999, the experimental design was a 3 N $\cdot$ $2^2$ PK factorial with two replicates, instead of the original $2^3$ NPK factorial in three replicates. The scheme had been changed, because the N applications, based on standard recommendations used in the Netherlands, seemed below optimum in the years 1975-1993. In Chapter 2, it was shown that this modification was justified, as the optimum N application rates in the period 1994-2002 surpassed N1, the originally recommended rates based on soil mineral N. Since 1994, N was applied at 0, 67 and 133% of N1 (= 100%). Table 3.1 presents the inputs of N, P and K.

The total size of the plots including border strips was 6 by 36 m, of which an area of 3 by 30 m was harvested; a portion of only 9 $m^2$ was collected separately for assessments of harvest index and chemical composition. Distinct samples were taken of grains and straw **(**spring-barley**)**, leaves and roots **(**sugar-beets**)**, while stalks plus leaves (= biomass) of silage-maize were sampled together. In the case of potato, only tubers were sampled because its foliage could not be harvested.

**Table 3.1.**
Crops, and input (I) of N, P and K from 1994 to 1999. P and K are expressed as elements. Also included are data on winter rains.

| Crop | Year | IN, kg $ha^{-1}$ | | IP, kg $ha^{-1}$ | IK, kg $ha^{-1}$ | Winter rain, mm[c] |
|---|---|---|---|---|---|---|
| | | At NL[a] | At NH[b] | | | |
| Spring-barley | 1994 | 57.5 | 115 | 25 | 41 | 418 |
| | 1998 | 40 | 80 | 25 | 41 | 347 |
| Sugar-beets | 1999 | 100 | 200 | 65 | 41 | 349 |
| Potatoes | 1995 | 160 | 320 | 87 | 41 | 478 |
| Silage maize | 1996 | 72 | 144 | 35 | 62 | 109 |
| | 1997 | 135 | 271 | 35 | 62 | 181 |

[a] NL low N input, at two thirds of recommended rate as based on soil mineral N
[b] NH high N input, at four thirds of recommended rate as based on soil mineral N
[c] Chapter 2, Table 2.3.

The samples were dried and chemically analysed for N, P and K according to standard procedures (Temminghoff & Houba, 2004) applied at Wageningen University.

*3.2.2. Nutrient uptake*

Crop uptake (U) of a nutrient was calculated as the product of the biomass (B) and the mass fraction (MF) of that nutrient in the dry biomass:

$$U = B \cdot MF / 1000 \qquad \text{(Eq. 3.1)}$$

Biomass (B) stands for the dry mass of the total crop. The units used in Equation 3.1 were kg ha$^{-1}$ for U and B, and g kg$^{-1}$ for MF.

Equation 3.1 was applied to silage maize and potato tubers. The uptake by potatoes was calculated by assuming that the nutrient amount in foliage equaled a certain portion of that in tubers; the values of these portions were derived from literature (Velthof & Van Erp, 1999).

For sugar-beets and spring-barley, nutrient uptake was calculated as the sum of the nutrients present in the economically interesting as well as in the remaining parts of the crop. Indicating the dry mass of the economically interesting parts (roots of sugar-beets, grains of spring-barley) by yield (Y), and that of the remaining crop parts (foliage of sugar-beets, straw of spring-barley) by 'stover' (S), for sugar-beets and spring-barley, uptake was calculated as:

$$U = (Y \cdot MF_y + S \cdot MF_s)/1000 \qquad \text{(Eq. 3.2)}$$

The sub-scripts y and s in Equation 3.2 stand for yield and stover.

The ratio of the dry mass of the yield to the dry mass of the total crop is the harvest index (HI), hence Y = HI · B, and S = (1-HI) · B. After substitution of Y and S in Equation 3.2, it reads:

$$U = [HI \cdot B \cdot MF_y + (1 - HI) \cdot B \cdot MF_s]/1000 \qquad \text{(Eq. 3.3)}$$

U and B are expressed in kg ha$^{-1}$ and MF in g kg$^{-1}$.

*3.2.3. Estimating the supply of available nitrogen in soil (SAN) and input (IAN)*

The maximum crop uptake of a nutrient from soil or from input (fertilizers or others) was considered to represent the available supply by or potential uptake from soil (SA) and by input (IA) (Janssen et al., 1990; Janssen, 2011). The uptake is maximum when the nutrient under study is the limiting growth factor, and the other growth factors are at an optimum level (Chikowo et al., 2010; Janssen et al., 1990). Accordingly, in the present study the maximum uptake of available N would be expected to show up in PK treatments receiving P and K. However, because input of P (IP) and input of K (IK) had little effect on crop performance (Chapter 2), P1K1 treatments were not automatically the ones with greater UN than P0K0 treatments. Therefore, simply the maximum UN of the four treatments (P0K0, P0K1, P1K0, P1K1) per level of N could have been taken for the estimation of the available supply of N, but to take into account that the distribution of UN was not always normal, ($\mu + 1.25 \cdot \sigma$) was considered a more reliable estimate of AN (an exception is discussed in Section 3.3.2) than the maximum UN of the four treatments.

$$AN = \mu + 1.25 \cdot \sigma \qquad \text{(Eq. 3.4a)}$$

In Eq. 3.4a, AN = amount of available N, $\mu$ = the average UN, and $\sigma$ is the standard deviation of the four UN values obtained at P0K0, P0K1, P1K0, and P1K1.

The reasoning is that at normal distribution, the maximum of four values equals the 0.8th percentile, and that is the value of (average + 1.25 times standard deviation: $\mu + 1.25 \cdot \sigma$).

Another consequence of the fact that P and K were not growth limiting was that available N (AN) and especially N uptake (UN) were the driving forces for crop growth and by that for the uptakes of P and K and for the responses to IP and IK. In graphs of available N (AN estimated as $\mu + 1.25 \cdot \sigma$) versus the input of N (IN), AN at N0 (IN = 0) was considered the available supply by soil (SAN), and the difference in ANs between NL (the lower IN) and N0 was used for the assessment of the availability fraction of input N ($AF_{IN}$):

$$AF_{IN} \text{ (in \%)} = 100 \cdot (AN_{NL} - AN_{N0})/IN_{NL} \qquad \text{(Eq. 3.4b)}$$

with AN and IN both in kg $ha^{-1}$.
The input of available N was calculated by:

$$IAN = AF_{IN} \cdot IN/100 \qquad \text{(Eq. 3.4c)}$$

where IAN is the input of available N and IN is the total input of N, both in kg $ha^{-1}$.
At NH (the higher IN), AN was calculated as:

$$AN_{NH} = AN_{N0} + AF_{IN} \cdot IN_{NH}/100 \qquad \text{(Eq. 3.4d)}$$

which, because $IN_{NH}$ was twice $IN_{NL}$ (Table 3.1) is equal to:

$$AN_{NH} = AN_{N0} + 2 \cdot (AN_{NL} - AN_{N0}) \qquad \text{(Eq. 3.4e)}$$

NL was taken as reference for the calculation of $AF_{IN}$, because at NL the relation between UN and IN was still close to linear. It was supposed that the availabality of input N (IN) was not affected by the rate of IN and that any diminishing uptake of N with increasing IN was caused by the inability of the crop to linearly increase the uptake of N because other factors than N supply became growth limiting.

### *3.2.4. Calculation of the effects of P and K on UN, yield, UP and UK*

The effects of P and K on UN were found via the relations between UN and IN, and the effects of P and K on yield, UP and UK were found via the relations between yield and UN, between UP and UN, and between UK and UN, respectively. As yields, UP, and UK were more directly related to UN than to IN, their values were better explained by UN than by IN. The relations were described with second order polynomials, separately for P1 or K1 (Eq. 3.5a) and for P0 or K0 (Eq. 3.5b), while

**Table 3.2.**
Crop yields (kg $ha^{-1}$) in relation to fertilizer treatments. Yields of spring-barley refer to grains at 15% moisture, yields of potato tubers, sugar-beet roots, and silage maize to dry matter. Significance level for (P1 - P0) is from Appendix 2, Table A.2.1. K1–K0 was never, and response to N was always significant.

| **Crop** | **Spring-barley** | | **S-beets** | **Potato** | **Silage maize** | | **Average** |
|---|---|---|---|---|---|---|---|
| **Year** | 1994 | 1998 | 1999 | 1995 | 1996 | 1997 | |
| **Treatment** | | | | | | | |
| N0P0K0 | 1055 | 2000 | 7169 | 2180 | 7393 | 5444 | *4207* |
| N0P0K1 | 1615 | 2560 | 7983 | 2621 | 5465 | 6055 | *4383* |
| N0P1K0 | 1310 | 2360 | 9706 | 3413 | 7927 | 7474 | *5365* |
| N0P1K1 | 1475 | 2050 | 7429 | 3854 | 9079 | 7082 | *5162* |
| *Average N0* | *1364* | *2243* | *8072* | *3017* | *7466* | *6514* | ***4779*** |
| NLP0K0 | 4025 | 5400 | 14194 | 8293 | 9996 | 10339 | *8708* |
| NLP0K1 | 4025 | 5190 | 12362 | 8634 | 11372 | 9729 | *8552* |
| NLP1K0 | 5115 | 5445 | 15556 | 10420 | 10629 | 11977 | *9857* |
| NLP1K1 | 5000 | 5670 | 15565 | 10706 | 12804 | 10683 | *10071* |
| *Average NL* | *4541* | *5426* | *14419* | *9513* | *11200* | *10682* | ***9297*** |
| NHP0K0 | 5720 | 5610 | 14560 | 10508 | 11120 | 8527 | *9341* |
| NHP0K1 | 5165 | 5895 | 18139 | 9475 | 10709 | 9171 | *9759* |
| NHP1K0 | 6530 | 5800 | 15330 | 11277 | 10198 | 11784 | *10153* |
| NHP1K1 | 5720 | 6355 | 15761 | **12161** | 9167 | 11363 | *10088* |
| *Average NH* | *5784* | *5915* | *15948* | *10855* | *10299* | *10211* | ***9835*** |
| Average P0 | 3601 | 4443 | 12401 | 6952 | 9343 | 8211 | ***7492*** |
| Average P1 | 4192 | 4613 | 13225 | 8639 | 9967 | 10061 | ***8449*** |
| P1-P0 | 591 | 170 | 824 | 1687 | 624 | 1850 | 957 |
| Significance (p) | 0.003 | 0.162 | 0.292 | 0.000 | 0.314 | 0.173 | |
| Average K0 | 3959 | 4436 | 12753 | 7682 | 9544 | 9258 | ***7938*** |
| Average K1 | 3833 | 4620 | 12873 | 7909 | 9766 | 9014 | ***8002*** |
| ***General average*** | ***3896*** | ***4528*** | ***12813*** | ***7795*** | ***9655*** | ***9136*** | |

$y_1 - y_0$, the difference between the two, represented the effect of P (or K) on the relation with UN (Eq. 3.5c):

$$y_1 = a_1 \cdot x^2 + b_1 \cdot x + c_1 \qquad \text{(Eq. 3.5a)}$$
$$y_0 = a_0 \cdot x^2 + b_0 \cdot x + c_0 \qquad \text{(Eq. 3.5b)}$$
$$y_1 - y_0 = (a_1 - a_0) \cdot x^2 + (b_1 - b_0) \cdot x + (c_1 - c_0) \qquad \text{(Eq. 3.5c)}$$

In these equations, y may stand for UN and x for IN, or y may stand for yield, UP or UK, and x for UN. Subscript 1 indicates level 1 of P or K, and subscript 0 indicates level 0 of P or K.
When these equations were used for y = UP or y = UK, the maximum value of Eq. 3.5b represented soil available P (SAP) or soil available K (SAK), respectively.
The maximum values of y in Equations 3.5a,b,c were obtained at $x_{opt}$, the optimum value of x, being calculated by setting the first derivative equal to 0:

$$dy/dx = 2 \cdot a \cdot x + b = 0, \text{ and} \qquad \text{(Eq. 3.5d)}$$
$$x_{opt} = - b/(2 \cdot a) \qquad \text{(Eq. 3.5e)}$$

The corresponding maximum value of y was found after substitution of $x_{opt}$ in the appropriate equation:

$$y_{max} = a \cdot x_{opt}^2 + b \cdot x_{opt} + c \qquad \text{(Eq. 3.5f)}$$

For a realistic calculation of $x_{opt}$, parameter *a* must be negative and parameter *b* must be positive, and the calculated $x_{opt}$ must lie within the range of observed x values.

### *3.2.5. Available amounts, actual uptake and uptake efficiency of N, P and K from soil and input*

Available N was estimated with Equation 3.4a, and available P and K were estimated with Equations 3.5a to 3.5f. Where the equations did not comply to the boundary conditions (negative parameter *a*; positive parameter *b*, $x_{opt}$ within the range of observed x values), pragmatic solutions were applied. This could include Equation 3.4a, but only at N application rates of NL and NH (Sections 3.3.4 and 3.3.6).

Actual uptake was found with equations 3.1 and 3.2 using observed yields and nutrient mass fractions. Uptake efficiency (%) was calculated as the ratio of actual uptake (U) to available amount (A):

$$UE = 100 \cdot U/A \qquad \text{(Eq. 3.6)}$$

## 3.3. Results

*3.3.1. Yields*

Table 3.2 presents crop yields of spring-barley, sugar-beet roots, potato tubers, and silage maize, in relation to fertilizer treatments. Responses to N were large. Yields of spring-barley, potatoes, and sugar-beets at N0 and NL were on average 38 and 88% of the yields at NH. The results of silage maize were rather irregular with N0 and NL yields of 68 and 107% of the NH yields. The coefficient of variation of maize yields was 29 and 25% in 1996 and 1997, respectively, while it was 13.5, 7.0, 15.6 and 10.5% for spring-barley 1994, 1998, sugar-beets 1999 and potatoes 1995, respectively, (Chapter 2, Appendix 2, Table A.2.1), reflecting the erratic pattern of maize growth.

Yields at P0 were about 89% of those at P1, but showed a variation from 66 to 113%. The difference between P0 and P1 yields was significant only for spring-barley in 1994 and for potatoes (Table 3.2). The ratio of the yields at K0 and K1 was on average 0.99, but the pattern was very irregular and the yield at K0 varied from 76 to 113% of that at K1. The difference between K1 and K0 yields was never significant. Maize yields were lower in 1997 than in 1996, and yields of spring-barley were lower in 1994 than in 1998. In both cases, the lower yields can be attributed to higher winter rainfall in those years (Table 3.1).

*3.3.2. Uptake of nitrogen (UN) in relation to input of N, P and K (IN, IP and IK)*

Table 3.3 shows that the average N uptake (UN) at N0 decreased in the order sugar-beets > silage maize > spring-barley > potato tubers, and varied roughly between 70 and 20 kg ha$^{-1}$. The general averages of UN (bottom line in Table 3.3) showed a second position for potato tubers, which must be ascribed to the larger N input to potato than to the other crops at NL and NH (Table 3.1). At each N level, application of P had for most crops a positive effect on UN, but it varied from negative to positive. On average, UN was about 9% higher at P1 than at P0, 12% for maize and 7% for the other crops. The effect of P on UN decreased in the order: at N0 > at NL > at NH, average ratios of [(UN at P0)/(UN at P1)] being 0.84 at N0, 0.91 at NL and 0.96 at NH, indicating that the effect of P on UN was the larger the smaller the supplies of N. The same phenomenon underlies the greater effect of P on UN for spring-barley in 1994 than in 1998 and for potatoes in 1995 than for sugar-beets in 1999 (see also Section 3.3.5).
Available N in Table 3.3 was calculated with Equations 3.4a – 3.4e. An exception was made in the case of spring-barley 1998, because there $AF_{IN}$ was more than 100%. Hence, $AN_{N0}$ and $AN_{NH}$ were recalculated as $AN_{NL}$ - IN and $AN_{NL}$ + IN, respectively.

**Table 3.3**
Uptake of N (kg $ha^{-1}$) and available N in relation to fertilizer treatments and crops. All values are averages of two replicates.

| **Crop** | **Spring-barley** | | **S-beets** | **Potato** | **Silage maize** | | **Average** |
|---|---|---|---|---|---|---|---|
| **Year** | 1994 | 1998 | 1999 | 1995 | 1996 | 1997 | |
| **Treatment** | | | | | | | |
| N0P0K0 | 17 | 29 | 58 | 17 | 71 | 26 | *36* |
| N0P0K1 | 21 | 34 | 70 | 21 | 45 | 40 | *39* |
| N0P1K0 | 21 | 33 | 81 | 28 | 84 | 37 | *47* |
| N0P1K1 | 24 | 27 | 59 | 29 | 76 | 39 | *42* |
| *Average N0* | *21* | *31* | *67* | *24* | *69* | *36* | ***41*** |
| Available N0[a] | 24 | 35, 44[c] | 80 | 31 | | | |
| NLP0K0 | 58 | 85 | 166 | 136 | 112 | 113 | *112* |
| NLP0K1 | 55 | 72 | 149 | 137 | 130 | 116 | *110* |
| NLP1K0 | 63 | 73 | 179 | 163 | 114 | 134 | *121* |
| NLP1K1 | 63 | 78 | 162 | 162 | 151 | 121 | *123* |
| *Average NL* | *60* | *77* | *164* | *150* | *127* | *121* | *117* |
| Available NL[a] | 65 | 84 | 179 | 168 | | | |
| NHP0K0 | 79 | 98 | 280 | 196 | 129 | 97 | *147* |
| NHP0K1 | 73 | 101 | 302 | 167 | 123 | 119 | *148* |
| NHP1K0 | 92 | 100 | 244 | 210 | 120 | 142 | *151* |
| NHP1K1 | 77 | 106 | 285 | 229 | 101 | 141 | *157* |
| *Average NH* | *81* | *101* | *278* | *201* | *118* | *125* | ***151*** |
| Available NH[b] | 105 | 134,124[d] | 278 | 306 | | | |
| Average at P0 | 50 | 70 | 171 | 112 | 102 | 85 | *98* |
| Average at P1 | 57 | 69 | 168 | 137 | 108 | 102 | *107* |
| Average at K0 | 55 | 70 | 168 | 125 | 105 | 92 | *103* |
| Average at K1 | 52 | 69 | 171 | 124 | 104 | 96 | *103* |
| ***General average*** | ***54*** | ***70*** | ***169*** | ***125*** | ***105*** | ***94*** | ***103*** |

[a] Available = Average UN +1.25 · σ. See Eq. 3.4a.
[b] Available NH = Available N0 + 2 · (Available NL - Available N0). See Eq. 3.4e
[c] $AN_{NL}$ – IN. See text [d] $AN_{NL}$ + IN. See text Section 3.3.2.
[e] N amounts in potato tuber plus foliage were calculated as 1.188 times N amounts in potato tuber (see text Section 3.2.2 and Velthof & Van Erp, 1999).

In Figure 3.1, available N and average nitrogen uptake (UN) were plotted versus nitrogen input (IN). The results of maize were considered too irregular (Table 3.3) to include them in the graph and in further calculations. Potatoes and spring-barley 1994 showed clearly diminishing UN responses to IN (Figure 3.1), but sugar-beets and spring-barley 1998 did not. Differences among treatments P1K1, P1K0, P0K1 and P0K0 were variable and small. Regression lines were calculated for all treatments together (so for the polynomial curves in Figure 3.1), as well as for P1 and P0, to arrive at estimates of ΔUN for P1-P0 (Equations 3.5a,b,c). In Table 3.4, parameters of the polynomial equations are shown as well as derived properties

$IN_{opt}$, $UN_{max}$ and $RF_{NL}$, the recovery fraction at NL. The differences in UN between K0 and K1 (not shown in Table 3.4) were very small, sometimes a little negative, sometimes a little positive, and the regression equations at K1 and K0 had an almost complete overlap.

The values of $IN_{opt}$ for the curves in Figure 3.1 were beyond the range of the actual IN (Table 3.4), indicating that theoretically UN could have been larger than the largest UN shown in Table 3.3, if more N had been applied. In the case of sugar-beets, there was no $IN_{opt}$ and hence no $UN_{max}$ because the quadratic term (*a*) of the polynomial regression equation had a positive sign, implying that UN increased more than proportional to IN. For potatoes, $UN_{max}$ at (P1 - P0) was relatively large (42 kg), compared to $UN_{max}$ for all treatments (198 kg) in Table 3.4.

The intercepts *c* of the linear regression equations for AN in Figure 3.1, considered the best estimates of available N supplies from the soil alone (SAN, soil available N), came down to 24, 44, 80 and 31 kg $ha^{-1}$ for spring-barley 1994, spring-barley 1998, sugar-beets, and potatoes, respectively, and were somewhat related (inversely) to the average rainfall (418, 347, 349 and 478 mm, respectively) between December and April of the corresponding preceeding winter (Table 3.1). The large winter rains in 1994 and 1995 may also have caused lower values of $RF_{NL}$ for spring-barley 1994 and potatoes (Table 3.4). Sugar-beets had an $RF_{NL}$ close to 100% and spring-barley 1998 of more than 100% (see footnote d in Table 3.4).

The slopes of the AN lines in Figure 3.1 represent the availability fraction of input N ($AF_{IN}$). In the case of spring-barley 1998, $AF_{IN}$ was more than 100%, which would point to a more than complete recovery of fertilizer N. Probably this recovery was accidental, because UN at N0 was low, especially of treatment N0P1K1 (see Table 3.3). Therefore, $AF_{IN}$ was set at 1 (see above). Estimated AN at NL was considered more reliable than estimated AN at N0, assuming that the so-called priming effect of applied N (Harmsen 2003; Jenkinson et al. 1985) had stimulated N uptake from soil N at NL.

*3.3.3. Yields (Y) in relation to uptake of N, and to input of P and K (UN, IP and IK)*

Figure 3.2 shows the procedure to estimate Δyield, caused by input of P, via the relations between yields (Y) and nitrogen uptake (UN). Such graphs are presented only for spring-barley 1994 and for potatoes because only for these crops Δyield by IP was significant. The regression equations were calculated (Equations 3.5a and 3.5b) for observed yields at P1 and P0, while the points and curves for Δyield were found by subtraction: P1-P0 (Equation 3.5c). In a same way regression equations at P1 and P0 and Δyield (= P1-P0) for spring-barley 1998 and sugar-beets were calculated, as well as for observed yields at K1 and K0 and for Δyield (= K1-K0).

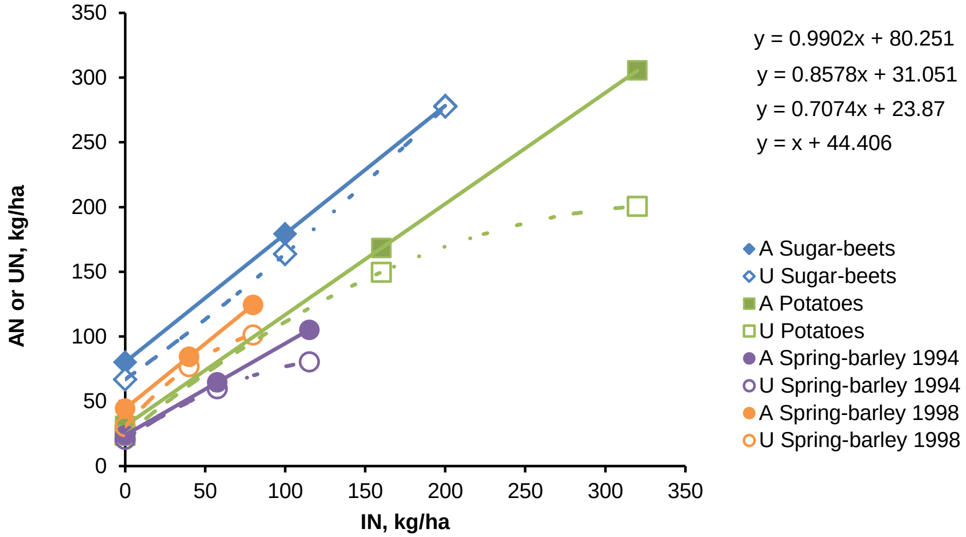


**Fig. 3.1**. Available N (Straight lines A) and average uptake of N (Polynomials U) in relation to N input (IN). Polynomials were calculated using all 12 treatments of a crop, four PK combinations at three N levels: from left to right at N0, NL and NH, while per treatment the average UN of two replicates was taken. Linear equations refer to AN. Parameters of polynomials and related properties are shown in Table 3.4. Uptake of potato refers to tuber plus foliage. N amounts in potato foliage were set at 0.188 times the quantities of N in potato tuber (see Section 3.2.2.).

**Table 3.4.**
Parameters and $R^2$ values of polynomial regression equations relating average UN and ΔUN (= P1–P0) to IN (curves of UN are shown but curves of ΔUN are not shown in Figure 3.1); calculated optimum IN and associated maximum UN; recovery fraction at NL ($RF_{NL}$, %). The parameters *a, b* and *c* refer to equations y= - $ax^2$ + *bx* + *c*, where y is UN and x is IN, both in kg $ha^{-1}$. Values of parameters *c* were rounded.

| Treatments | Crops | -*a* | *b* | *c* | $R^2$ | $IN_{opt}$ | $UN_{max}$ | $RF_{NL}$ |
|---|---|---|---|---|---|---|---|---|
| All | S-barley 94 | 0.0027 | 0.8344 | 21 | 0.9634 | 155[b] | 85[b] | 68 |
| | S-barley 98 | 0.0068 | 1.4290 | 31 | 0.9828 | 105[b] | 105[b] | 116[d] |
| | S-beets 99 | -0.0008 | 0.8841 | 67 | 0.9716 | N.A.[c] | N.A.[c] | 97 |
| | Potatoes 95[a] | 0.0015 | 1.0226 | 24 | 0.9599 | 341[b] | 198[b] | 79 |
| P1 – P0 | S-barley 94 | 0.0002 | 0.0691 | 3 | | 173[b] | 9 | |
| | S-barley 98 | -0.0026 | -0.1496 | -1 | | N.A.[c] | N.A.[c] | |
| | S-beets 99 | 0.0020 | 0.2461 | 7 | | 62 | 14 | |
| | Potatoes 95[a] | 0.0001 | 0.1134 | 10 | | 567[b] | 42[b] | |

[a] Tubers and foliage; N amounts in potato foliage were calculated as 0.188 times N in potato tuber (see text 3.2.2 and Velthof & Van Erp, 1999).
[b] Although calculated values of $IN_{opt}$ were found by extrapolation of the regression equations beyond actual IN, values of $UN_{max}$ were calculated.
[c] N.A. not applicable since the quadratic term (*a*) of the polynomial regression equation has a positive sign
[d] $RF_{NL}$ is more than 100% mainly because of low UN of treatment N0P1K1 and high UN of treatment NLP0K0 (see Table 3.3)

Regression coefficients and related properties are given in Table 3.5. Only the values for spring-barley 1998 and sugar-beets in column $UN_m$ were within the range of observed UNs and had realistic maximum yields around 6000 and 16000 kg $ha^{-1}$, respectively. The values of '*–a*' of the lines of spring-barley 1994 and potatoes were comparatively small (Table 3.5) resulting in calculated values of $UN_m$ far beyond the highest observed UNs of 92 and 229 kg $ha^{-1}$, respectively (Table 3.3). Most values of $UN_m$ for maximum yield in Table 3.5 exceed those of $UN_{max}$ in Table 3.4, implying that N uptake often was not sufficient to reach the theoretically highest possible yields.

### *3.3.4. Phosphorus uptake (UP) and availability (AP) in relation to input of N (IN), input of P (IP), and uptake of N (UN)*

The uptake of P was strongly affected by IN, even more than by IP (Table 3.6). The data of silage maize were very irregular, especially in 1996. Nutrient mass fractions change during growth, which makes it difficult to sample and analyse silage maize in a representative way and creates big at-random variations. Differences in

**Table 3.5.**
Parameters and $R^2$ values of the polynomial regression equations relating yield to UN at P1, P0, K1, K0, calculated $UN_m$ for maximum or minimum yield ($Y_m$). The parameters a, b and c refer to equations $y = ax^2 + bx + c$, where y is yield and x is UN, both in kg $ha^{-1}$. Values of parameters b and c are rounded. $R^2$ values of ΔY (=P1-P0) are 1.0, because ΔY is the difference between two polynomials.

| Crop | | -a | b | c | $R^2$ | $UN_m$ | $Y_m$ |
|---|---|---|---|---|---|---|---|
| Spring-barley | P1 | 0.5467 | 135 | -1323 | 0.9979 | 123[b] | 7009[b] |
| 1994 | P0 | 0.0297 | 75 | -84 | 0.9956 | 1261[b] | 47145[b] |
| | P1-P0 | 0.5170 | 60 | -1239 | | 58 | 507 |
| | K1 | 0.2076 | 95 | -448 | 0.9865 | 229[b] | 10417[b] |
| | K0 | 0.2745 | 103 | -688 | 0.9899 | 188[b] | 9059[b] |
| Spring-barley | P1 | 0.6554 | 140 | -1374 | 0.9884 | 107 | 6150 |
| 1998 | P0 | 0.6718 | 138 | -1387 | 0.9951 | 103 | 5747 |
| | K1 | 0.5753 | 129 | -1052 | 0.9925 | 112[b] | 6206[b] |
| | K0 | 0.8634 | 163 | -2039 | 0.9937 | 95 | 5688 |
| Sugar-beets | P1 | 0.3082 | 140 | 405 | 0.9799 | 227 | 16304 |
| 1999 | P0 | 0.1187 | 88 | 2402 | 0.9942 | 371[b] | 18727[b] |
| | K1 | 0.1860 | 107 | 1608 | 0.9356 | 289 | 17109 |
| | K0 | 0.3290 | 143 | 96 | 0.9907 | 217 | 15582 |
| Potatoes [a] | P1 | 0.1503 | 80 | 1480 | 0.9961 | 266[b] | 12119[b] |
| 1995 | P0 | 0.0960 | 66 | 1218 | 0.9985 | 344[b] | 12548[b] |
| | P1–P0 | 0.0543 | 14 | 262 | | 129 | 1167 |
| | K1 | 0.0737 | 63 | 1687 | 0.9813 | 425[b] | 14977[b] |
| | K0 | 0.1046 | 69 | 1286 | 0.9885 | 331[b] | 12714[b] |

[a] Tubers and foliage; N amounts in potato foliage were calculated as 0.188 times N in potato tuber (see text 3.2.2 and Velthof & Van Erp, 1999).
[b] Although calculated values of $UN_m$ were found by extrapolation of the regression equations beyond actual UN, values of $Y_m$ were calculated for the sake of completeness and curiosity.

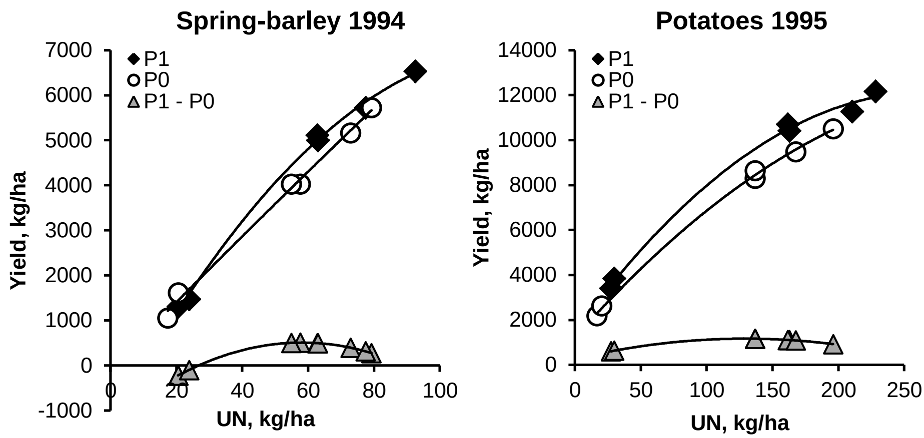


**Fig. 3.2.** Relationship between observed yields and uptakes of N (UN) at P1 and P0 for spring-barley 1994 and potatoes 1995. The regression equation of $\Delta$yield (= P1 – P0) is equal to the difference between the equations at P1 and P0.

harvest time, in 1996 after 167 days (29$^{th}$ October), and in 1997 after 131 days (7$^{th}$ October) further contributed to nutrient uptake differences between 1996 and 1997. The data for maize in Table 3.6 were therefore considered unreliable, once more justifying the exclusion of maize from further analysis on nutrient uptake and use efficiency.

Uptakes of P at P0 were about 73% of those at P1 (Table 3.6), indicating that the effect of P input (IP) was stronger on UP than on yield. If the silage maize data were left out, UP at P0 was on average 71% of UP at P1. At P0 as well as at P1, UP increased with increasing levels of IN, except for the two years with silage maize (Table 3.6).

Maximum uptake of P from the soil alone (SAP) was between 23 and 29 kg ha$^{-1}$, with the largest value for sugar-beets (Available at P0 in Table 3.6). The increase in UP at P0, going from N0 to NL to NH, suggests that probably still higher P uptakes from the soil alone would have been possible if N application rates had been higher than NH. In the case of sugar-beets, UP at NL was remarkably low (16.4) which was caused by very low mass fractions of P (MFP) in treatment NLP0K1 and rather low in treatment NLP0K0 (not shown). Estimating MFP via a missing-value procedure for the treatment with the lowest MFP, resulted in an UP of 19.6 kg ha$^{-1}$ for NLP0, and this value was further used. Available P was calculated, similar to Equation 3.4a, by: AP = $\mu + 1.25 \cdot \sigma$, where $\mu$ and $\sigma$ were the averages and standard deviations of UP data at NL and NH.

Data of UP at N0 were not included in the calculation of AP, because at N0 deficiency of N limited uptake of P, and made estimation of available P impossible.

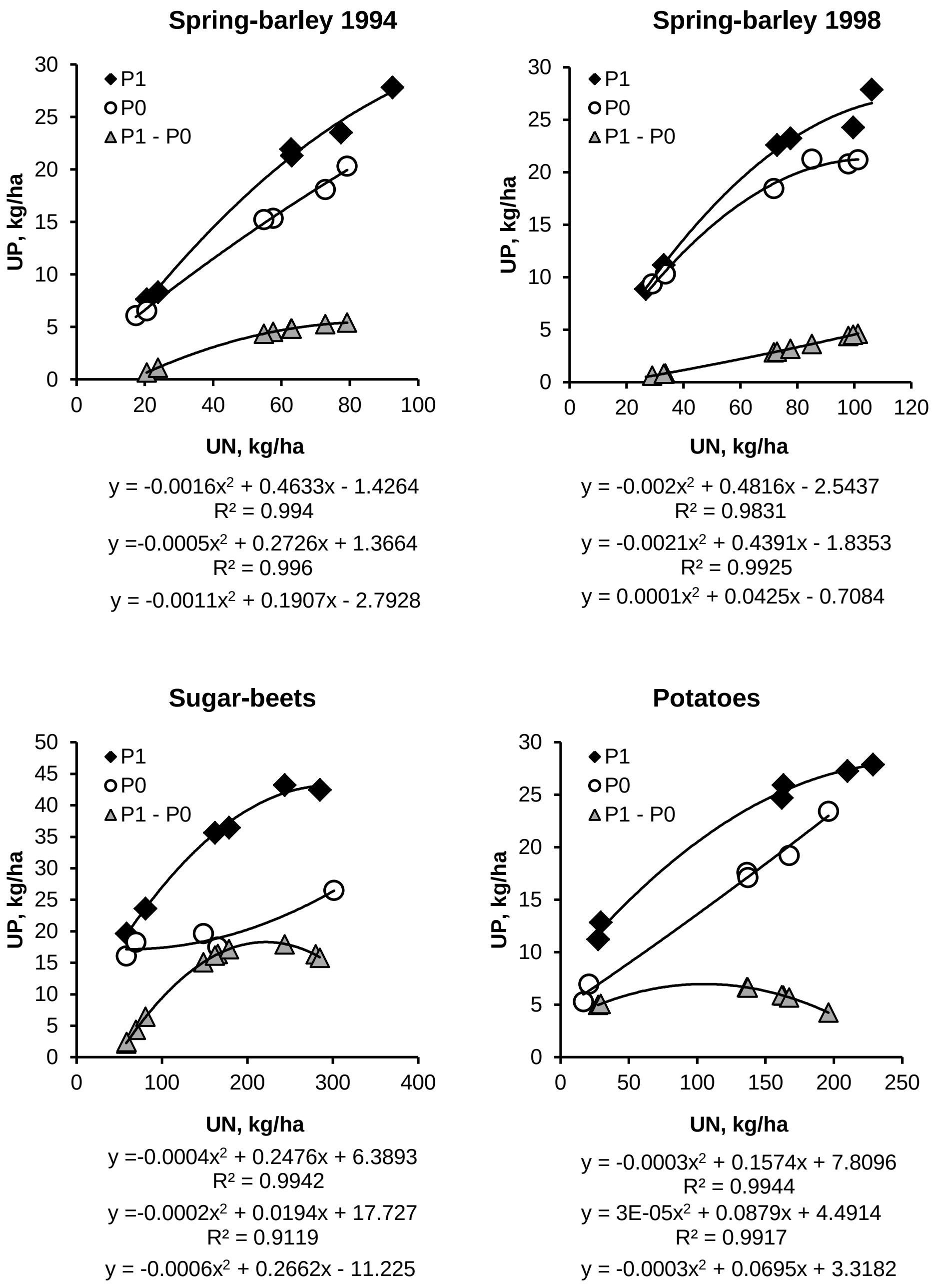


**Fig. 3.3.** Observed P uptake (UP) at P1 and P0, and calculated ΔUP (= P1 – P0), in relation to UN. Uptake of potato refers to tuber plus foliage. N and P amounts in potato foliage were set at 0.188 and 0.164 times the quantities of N and P in potato tuber (see text Section 3.2.2.). Related values of $UN_m$ and $UP_m$ are shown in Table 3.7.

**Table 3.6.**
Uptake of P (kg $ha^{-1}$) in relation to fertilizer N and P treatments and crops. All values are averages of four (treatments K0 and K1; two replicates).

| **Crop** | **Spring-barley** | | **S-beets** | **Potato**[d] | **Silage maize** | | **Average**[e] |
|---|---|---|---|---|---|---|---|
| **Year** | 1994 | 1998 | 1999 | 1995 | 1996 | 1997 | |
| **Treatment** | | | | | | | |
| N0P0 | 6.3 | 9.8 | 17.2 | 6.2 | 19.5 | 12.7 | *9.9* |
| NLP0 | 15.3 | 19.8 | 16.4[c] | 17.4 | 13.9 | 10.9 | *17.5* |
| NHP0 | 19.2 | 21.0 | 27.1 | 21.3 | 14.7 | 10.0 | *22.2* |
| *Average at P0* | *13.6* | *16.9* | *20.2* | *15.0* | *16.0* | *11.2* | ***16.4*** |
| Available at P0[a] | 20.3 | 22.1 | 29.1 | 22.9 | | | **23.6** |
| N0P1 | 8.0 | 10.0 | 21.5 | 12.1 | 19.6 | 17.6 | *12.9* |
| NLP1 | 21.6 | 22.9 | 36.1 | 25.3 | 18.9 | 15.3 | *26.5* |
| NHP1 | 25.7 | 26.1 | 42.8 | 27.6 | 14.2 | 15.4 | *30.6* |
| *Average at P1* | *18.4* | *19.7* | *33.5* | *21.7* | *17.6* | *16.1* | ***23.3*** |
| Available at P1[a] | 27.3 | 27.4 | 44.4 | 28.2 | | | **31.8** |
| P1 – P0 at | | | | | | | |
| N0 | 1.7 | 0.2 | 4.4 | 5.9 | 0.0 | 4.9 | *3.1* |
| NL | 6.3 | 3.1 | 19.7 | 8.0 | 4.9 | 4.3 | *9.3* |
| NH | 6.5 | 5.1 | 15.7 | 6.3 | -0.5 | 5.4 | *8.4* |
| *Average P1 –P0* | *4.8* | *2.8* | *13.3* | *6.7* | *1.5* | *4.9* | ***6.9*** |
| Available P1-P0 | 7.0 | 5.4 | 15.3 | 5.3 | | | **8.3** |
| $AF_{IP}$, % [b] | 28.1 | 21.4 | 24 | 6 | | | **19.9** |

[a] Available P was calculated, similar to Equation 4a, as: $AP = \mu + 1.25 \cdot \sigma$, using the UP data at NL and NH
[b] $AF_{IP}$% = available fraction of input P = 100 · available (P1 –P0)/IP. Values of IP in Table 3.1.
[c] The low UP by sugar-beets at NLP0 was caused by low P fractions (MFP) in treatment NLP0K1. Calculation of MFP with a missing-value procedure for NLP0K1 resulted in an UP of 19.6 kg $ha^{-1}$.
[d] Tubers and foliage; P amounts in potato foliage were calculated as 0.164 times P in potato tubers (see text Section 3.2.2 and Velthof & Van Erp, 1999).
[e] Exclusive maize

Figure 3.3 presents the relations between UP and UN and the associated polynomials (Equations 3.5a,b,c), separately for P1, P0 and (P1 - P0). Most of the calculated corresponding values of $UN_m$ in Table 3.7 were somewhat larger than $UN_{max}$ in Table 3.4. These results suggest that P uptake could have been higher if UNs had been higher than the observed UNs. The values of $UN_m$ for maximum $\Delta$UP (P1 – P0), however, are within the range of observed UNs, with the exception of spring-barley 1998 (Table 3.7, Figure 3.3). The maximum values of $UP_m$ for P1-P0 in Table 3.7 were 6.4, 18.3, and 7.3 kg $ha^{-1}$ for spring-barley 1994, sugar-beets and potatoes, respectively. They correspond to recovery fractions ($RF_{IP}$) of 25.6, 28.2 and 8.4 % of the respective P quantities applied. For sugar-beets and potatoes $RF_{IP}$ is a little higher than $AF_{IP}$ (Table 3.6), because $UP_m$ in Table 3.7 was calculated exactly at the (calculated) optimum of UN while $AF_{IP}$ deals with all observed UP values at NL and NH situated left or right from the optimum (Figure 3.3). From comparison of P1–P0 curves for yields in Figures 3.2 with P1–P0 curves for UP in Figure 3.3, it is learnt that the effect of P input (IP) was relatively greater for UP than for yield.

*3.3.5. Dissection of IP effects, on yield and on P uptake, into an indirect and a direct effect*

Where the input of P increased the uptake of N (Table 3.3), the response to IP consisted partly of an indirect effect caused by differences in N uptake (UN) at equal inputs of N, and partly of a direct effect caused by differences between P1 and P0 at equal uptakes of N. The latter responses are seen for yields in Figure 3.2 and for UP in Figure 3.3. In Appendix 3, Section A.3.1, it is illustrated how the response to P input could be dissected into an indirect and a direct response. As effects of IP on UN and on yield were visible only for spring-barley 1994 and potatoes (Tables 3.3 and 3.4), the indirect and direct effects of IP on yield and on UP are shown just for these crops in Table 3.8. The indirect effects on yield, $\Delta Y_{(UN)}$, were sometimes a little larger and sometimes a little smaller than the direct effects, $\Delta Y_{(P1\text{-}P0)}$. On P uptake, however, the indirect effects, $\Delta UP_{(UN)}$, were in 5 of the 6 cases smaller than the direct effects, $\Delta UP_{(P1\text{-}P0)}$.

*3.3.6. Potassium uptake (UK) and availability (AK) in relation to input of N (IN), input of K (IK), and uptake of N (UN)*

The uptake of K was affected by IN as well as by IK (Table 3.9). The UK data of silage maize were irregular, again especially in 1996; it is another good reason to exclude maize from further analysis on nutrient uptake. When maize is left out, uptakes of K at K0 were about 89% of those at K1 (Table 3.9).

Soil available K (Available at K0 in Table 3.9) was between 95 and 450 kg $ha^{-1}$, with the highest value for sugar-beets. The increase in UK at K0, going from N0 to NL to NH, suggests that at IN larger than NH still more K would have been taken up from the soil alone. The uptake of 410 kg $ha^{-1}$ by sugar-beets at NHK0 in Table 3.9, however, likely was an outlier; it was the average of 461 (at NHP0K0) and 359 (at NHP1K0) kg $ha^{-1}$ (Appendix 3, Table A.3.1). The extreme position of Treatment NHP0K0 was the reason why Treatment NHP0K0 was not included in the K0 regression equation of UK versus UN (Figure 3.4). According to the regression equation of UK at K0, the maximum UK by sugar-beets from the soil alone is 377 kg $ha^{-1}$ to be reached at an $UN_m$ of 309 kg $ha^{-1}$ (Table 3.10), which is beyond the observed values of UN and UK at K0.

Available K was calculated, similar to Equation 3.4a, by: $AK = \mu + 1.25 \cdot \sigma$, where $\mu$ and $\sigma$ were the averages and standard deviations of UK data at NL and NH. As for UP, data of UK at N0 were not included because deficiency of N prohibited good estimates of available K at N0.

**Table 3.7.**
Calculated values of N uptake ($UN_m$) for maximum or minimum P uptake ($UP_m$). Calculations were made with regression equations shown in Figure 3.3.

| | **At P1** | | **At P0** | | **P1-P0** | |
|---|---|---|---|---|---|---|
| | $UN_m$ | $UP_m$ | $UN_m$ | $UP_m$ | $UN_m$ | $UP_m$ |
| Spring-barley 1994 | 143 | 37.4 | 267[b] | 44.5[b] | 86 | 6.4 |
| Spring-barley 1998 | 123 | 31.9 | 103 | 24.5 | -125[bd] | -4.0[bd] |
| Sugar-beets | 310 | 44.7 | 48.5[c] | 17.3[c] | 221 | 18.3 |
| Potatoes [a] | 268 | 28.5 | -1465[d] | -60[d] | 116 | 7.3 |

[a] Tubers and foliage; N and P amounts in potato foliage were calculated as 0.188 and 0.164 times the quantities of N and P in potato tuber (see text Section 3.2.2 and Velthof & Van Erp, 1999)
[b] Not realistic as UP is almost linearly related to UN.
[c] UN and UP refer to minimum values of UP and are uncertain because of the low values of measured UP at NLP0 (Table 3.6; Figure 3.3)
[d] Since the quadratic term (*a*) of the polynomial regression equation has a positive sign, $UN_m$ and $UP_m$ refer to minimum values of UP, moreover they are not realistic as they are negative.

**Table 3.8.**
Dissection of the effect of P input (IP) on yield and on P uptake into an indirect effect of P via increased UN as denoted by $\Delta Y_{(UN)}$ and $\Delta UP_{(UN)}$, and a direct effect as denoted by $\Delta Y_{(P1-P0)}$ and $\Delta UP_{(P1-P0)}$ representing the difference in Y or in UP between P1 and P0 at a same level of UN. All values are in kg ha$^{-1}$. For explanation, see Appendix 3, Section A.3.1.

| | **IP effect on** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | **N uptake** | **Yield (Y)** | | | **P uptake (UP)** | | | **ΔY/ ΔUP** |
| | UN | $\Delta Y_{(UN)}$ | $\Delta Y_{(P1-P0)}$ | Total | $\Delta UP_{(UN)}$ | $\Delta UP_{(P1-P0)}$ | Total | Total |
| **IN level** | *Spring-barley 1994* | | | | | | | |
| N0 | 3.23 | 238 | -161 | 77.3 | 0.81 | 0.90 | 1.71 | 45.2 |
| NL | 6.64 | 474 | 495 | 969 | 1.41 | 4.85 | 6.26 | 154.6 |
| NH | 8.91 | 623 | 104 | 727 | 1.69 | 5.41 | 7.09 | 102.5 |
| | *Potatoes 1995* | | | | | | | |
| N0 | 9.8 | 601 | 617 | 1218 | 0.87 | 5.03 | 5.91 | 206.3 |
| NL | 25.8 | 960 | 1106 | 2066 | 2.50 | 5.90 | 8.39 | 246.1 |
| NH | 37.6 | 1043 | 720 | 1763 | 3.75 | 2.66 | 6.41 | 275.0 |

In all four years, the uptake of K from K input (K1 – K0) increased with increasing UN, but it was smaller than the uptake of K from the soil (K0) at a same UN (Figure 3.4). The largest difference (K1-K0) by sugar-beets of 79 kg (Figure 3.4), found at an UN of 244 kg ha$^{-1}$, was even higher than the input of 41 kg K per ha. This may have been a consequence of the variation in measured UK values, but it also may indicate that sugar-beets were able to take up, besides the most recently applied fertilizer K, any residual fertilizer K remaining after other crops.

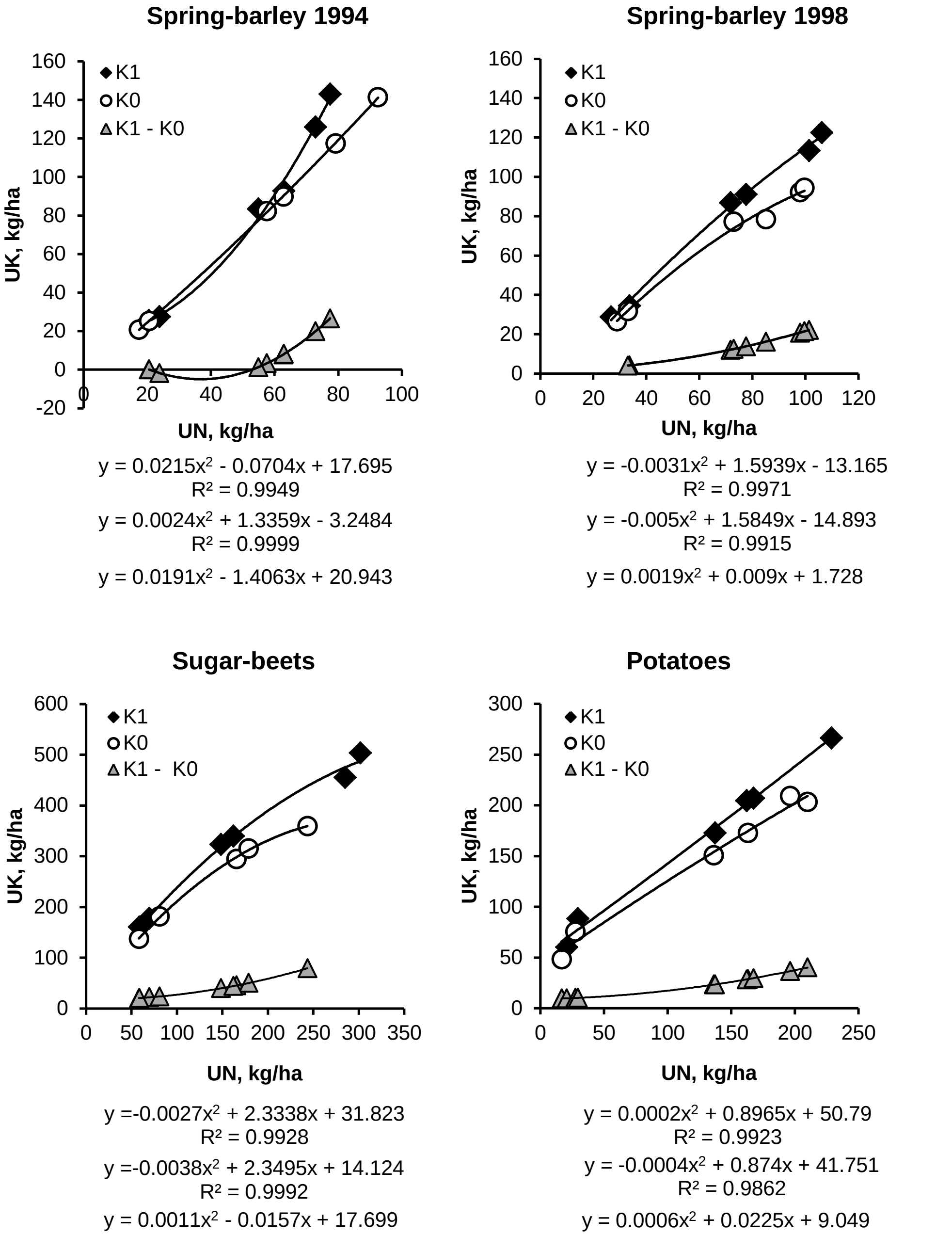


**Fig. 3.4.** Measured K uptake (UK) at K1 and K0, and calculated ΔUK (= K1 – K0), in relation to UN. Uptake of potato refers to tuber plus foliage. N and K amounts in potato foliage are set at 0.188 and 0.195 times the quantities of N and K in potato tuber (see text 3.2.2.).

**Table 3.9.**
Uptake of K (kg $ha^{-1}$) in relation to fertilizer treatments and crops. All values are averages of four (treatments P0 and P1; two replicates).

| **Crop** | **Spring-barley** | | **S-beets** | **Potato**[d] | **Silage maize** | | **Average**[e] |
|---|---|---|---|---|---|---|---|
| **Year** | 1994 | 1998 | 1999 | 1995 | 1996 | 1997 | |
| **Treatment** | | | | | | | |
| N0K0 | 23.0 | 29.2 | 158.9 | 61.7 | 74.8 | 146.8 | 68.2 |
| NLK0 | 86.1 | 77.9 | 304.8 | 161.7 | 123.1 | 138.7 | 157.6 |
| NHK0 | 129.4 | 93.3 | 410.2 | 206.2 | 132.0 | 146.5 | 209.8 |
| *Average at K0* | *79.5* | *66.8* | *291.3* | *143.2* | *110.0* | *144.0* | ***145.2*** |
| Available at K0[a] | 141.5 | 96.8 | 450.2 | 218 | | | **226.6** |
| N0K1 | 26.5 | 37.3 | 169.0 | 74.2 | 115.5 | 147.5 | 76.8 |
| NLK1 | 88.1 | 104.6 | 331.3 | 188.7 | 135.1 | 174.1 | 178.2 |
| NHK1 | 134.4 | 138.7 | 479.3 | 236.7 | 153.6 | 196.2 | 247.3 |
| *Average at K1* | *83.0* | *79.5* | *326.5* | *166.5* | *134.7* | *172.6* | ***163.9*** |
| Available at K1 | 146.2 | 125.0 | 515, 491[b] | 262, 259[b] | | | **255.3** |
| K1 – K0 at | | | | | | | |
| N0 | 3.6 | 2.5 | 10.1 | 12.4 | 40.7 | 0.7 | 7.2 |
| NL | 2.0 | 11.0 | 26.5 | 27.0 | 12 | 35.4 | 16.6 |
| NH | 5.1 | 24.6 | 69.1 | 30.5 | 21.6 | 49.7 | 32.3 |
| *Average K1 –K0* | *3.5* | *12.7* | *35.2* | *23.3* | *24.8* | *28.6* | ***18.7*** |
| Available K1-K0 | 4.7 | 28.5 | 65, 41[b] | 44,41[b] | | | **28.8** |
| $AF_{IK}$% [c] | 11.4 | 68.8 | 159, 100[b] | 103, 100[b] | | | **70.1** |

[a] Available K was calculated, similar to Equation 3.4a, as: $AK = \mu + 1.25 \cdot \sigma$, using the UK data at NL and NH
[b] $AK_{K1} = AK_{K0} + IK$
[c] $AF_{IK}$% = available fraction of input K = 100 · available (K1 –K0)/IK. Values of IK in Table 3.1.
[d] Tubers and foliage; K amounts in potato foliage were calculated as 0.195 times K in potato tubers (see text Section 3.2.2 and Velthof & Van Erp, 1999).
[e] Exclusive maize

**Table 3.10.**
Calculated values of N uptake ($UN_m$) needed for maximum or minimum K uptake ($UK_m$). Calculations are made with regression equations shown in Figure 3.4.

| | **At K1** | | **At K0** | | **K1-K0** | |
|---|---|---|---|---|---|---|
| | $UN_m$ | $UK_m$ | $UN_m$ | $UK_m$ | $UN_m$ | $UK_m$ |
| Spring-barley 1994 | 0.001[b] | 21[b] | -271[bc] | -217[bc] | 37[b] | -6[b] |
| Spring-barley 1998 | 253[d] | 222[d] | 158[d] | 130[d] | -2[bc] | 2[b] |
| Sugar-beets | 432[d] | 536[d] | 309[d] | 377[d] | 7[b] | 18[b] |
| Potatoes [a] | -2241[bc] | -954[bc] | 1093[d] | 519[d] | -19[bc] | 9[b] |

[a] Tubers and foliage; N and K amounts in potato foliage were calculated as 0.188 and 0.195 times the quantities of N and K in potato tuber (see text Section 3.2.2 and Velthof & Van Erp, 1999)
[b] Since the quadratic term (*a*) of the polynomial regression equation has a positive sign, $UN_m$ and $UK_m$ refer to minimum values of UK.
[c] Not realistic as they are negative.
[d] $UN_m$ (far) beyond measured UN

The upmost UKs from input K calculated for potatoes and spring-barley were about 40 kg and 25 kg $ha^{-1}$ (Figure 3.4), corresponding to fertilizer K recovery fractions of around 100% for potatoes and of 61% for spring-barley. Despite the uncertainties involved, these calculations point to a very high or even complete recovery of input K by the K demanding starch and sugar-producing crops (potatoes, sugar-beets). This implies that the absence of significant effects of input K on yields (Chapter 2; Table 2.2) cannot be ascribed to a failure of crops to take up fertilizer K or to leaching losses of fertilizer K.

*3.3.7 Dissection of IK effects, on yield and K uptake, into an indirect and a direct effect*

For the sake of completeness, also for K an analysis was made of the indirect and direct effects of fertilizer K on yield and on UK. In agreement with the observation that application of K had little or no effect on the uptake of N (Table 3.3), the indirect effects of input K on yield via a stimulus in UN were much smaller than the direct effects caused by the difference between K1 and K0 at a same level of UN (not shown). Also for the uptake of K, the indirect effects of IK were smaller than the direct effects at a same level of UN, but the total effect of IK on UK was always positive.

*3.3.8. Supplies of available N, P and K in soil and input*

Table 3.11 gives a summary of the soil supplies of available N, P and K and available fractions ($AF_I$) of input nutrients. The soil supplies of available N were estimated (SAN) as the intercepts of the AN lines in Figure 3.1. The values of $UP_m$ at P0 in Table 3.7 would represent the maximum uptake of UP from the soil alone (SAP), but only the value of spring-barley 1998, being 25 kg $ha^{-1}$, was a realistic one because there $UN_m$ was within the range of observed UNs. The quantities of 'Available at P0' were taken as the best possible estimates, although underestimates, of SAP (Table 3.6).

A similar problem as for SAP existed for the estimation of SAK; only for spring-barley 1998 and sugar-beets the values of $UK_m$ (130) and 377 at K0 (Table 3.10) were found at UNs within the observed range. Therefore, the quantities of 'Available at K0' were taken as the best possible estimates of SAK (Table 3.9). These values likely underestimated SAK because UK still strongly increased with increasing UN in Figure 3.4.

**Table 3.11.**
Soil available (SA) N, P and K, and available fractions ($AF_I$) of input N, P and K (% of the applied amount).

| | SA, kg ha- | | | $AF_I$, % | | |
|---|---|---|---|---|---|---|
| **Crop** | N | P | K | N | P | K |
| Spring-barley 94 | 24 | 20 | 141 | 70 | 28 | 11 |
| Spring-barley 98 | 44 | 22 | 97 | 100 | 21 | 69 |
| Sugar-beets | 80 | 29 | 450 | 99 | 24 | 100 |
| Potatoes | 31 | 23 | 218 | 86 | 6 | 100 |

Rounded $AF_{IN}$ values were 70, 100, 99 and 86% for spring-barley 1994, spring-barley 1998, sugar-beets and potatoes, respectively, being the slopes of AN lines in Figure 3.1. The available fractions of input P ($AF_{IP}$) and input K ($AF_{IK}$) were presented in Table 3.6 and 3.9, respectively. In Table 3.9, it was estimated that $AF_{IK}$ was 100% for sugar-beets and potatoes, and 11 and 69% for spring-barley in 1994 and 1998, respectively. Because 1994 was a rather extreme year, a value of 69% of $AF_{IK}$ for spring-barley likely is the more reliable one.

### *3.3.9. Uptake efficiency of available N, P and K in soil and input*

The data of Tables 3.3, 3.6 and 3.9 on available N, P and K, respectively, were used to calculate the amounts of available nutrients and the uptake efficiency (UE) in Appendix 3, Table A.3.1. In Chapter 4 and Appendix 4, they were used for the calculation of balanced supplies of crop available N, P and K. As the pattern of the relations between uptake efficiency (UE) and fertilizer treatments was similar for the four crops, Table A.3.1 (Appendix 3) was summarized by averaging UE across the four crops per application level of N (N0, NL, NH) (Figure 3.5). At N0, UEN was much higher than UEP and UEK. At NL, UEN was somewhat higher than at N0 and at NH. At N0, too little N was available for satisfactory root development which prohibited ‘normal’ uptake of nutrients and corresponding crop growth. At NL, UE of each of the three nutrients was much higher than at N0. At NH, UEP and UEK further increased, but UEN did not. Likely other growth factors than available N became growth limiting resulting in diminishing actual N uptake while the amount of the available N increased linearly with increasing IN.

At N0, shortage of N limited growth and by that uptake of available P and K. Actual uptake of P and K increased with increasing levels of N input and also UEP and UEK increased, because the (estimated) quantities of available P and K remained the same at N0, NL and NH.

## 3.4. Discussion

### *3.4.1. General*

As concluded before (Spiertz & Ellen, 1978; Chapter 2), nitrogen was the overriding growth-limiting factor on this former sea-bottom soil. This chapter showed that nitrogen uptake (UN) differed among crops and years, that UN was not affected by K application (IK) and only a little by the application of P (IP). An influence of IP on UN was seen only in the case of potatoes in 1995 and of spring-barley 1994 (Table 3.3).

The uptake of P and K from the soil alone, shown as UP at P0 in Figure 3.3, and as UK at K0 in Figure 3.4, seemed practically unlimited. This made it impossible to make realistic estimates of the available amounts of P and K present in the soil. The values of SAP and SAK in Table 3.11 should therefore be interpreted as the best estimates at treatments NL and NH. Despite the huge P and K uptakes from the soil, the crops took up P and K from the inputs too. It is obvious that the erratic and small yield responses to IP, and the absence of yield responses to IK, were not caused by P or K fixation processes in the soil or losses from the soil, making uptake of input P and K impossible.

The original intention of this long-term trial was to find out how long crop yields could be maintained without application of fertilizer nutrients, in other words how long it would take before these rich soils got exhausted (Chapter 1). The soil of the experimental farm had been planted to crops since 1960 (Chapter 2, Section 2.2.1). At the end of the trial (2002), i.e. after more than forty years of crop cultivation, no shortages of K were visible and scarcities of P were hardly significant. This implies that it was still impossible to answer the question how long it would take before the soil would be depleted of P and K in case these nutrients were not applied.

### *3.4.2. Availability and actual uptake of nutrients*

In this chapter, the available amount (A) of a nutrient was estimated as the maximum uptake of that nutrient when no other nutrients and growth factors were limiting. For nitrogen, these conditions were satisfied at N0 irrespective P and K treatments, as soil P and soil K levels were high. Hence, available N (AN) could be estimated as the maximum UN found at the four PK combinations and calculated as ($\mu + 1.25 \cdot \sigma$) with Equation 3.4a.

The observed difference in estimated AN between NL and N0 was sometimes larger than the quantity of N applied at NL. This was ascribed to the so-called priming effect (Harmsen 2003; Jenkinson et al. 1985). In these cases, the estimation of AN at NL was considered more reliable than the estimation of AN at N0; therefore $AN_{N0}$ was calculated by $AN_{NL}$ – IN.

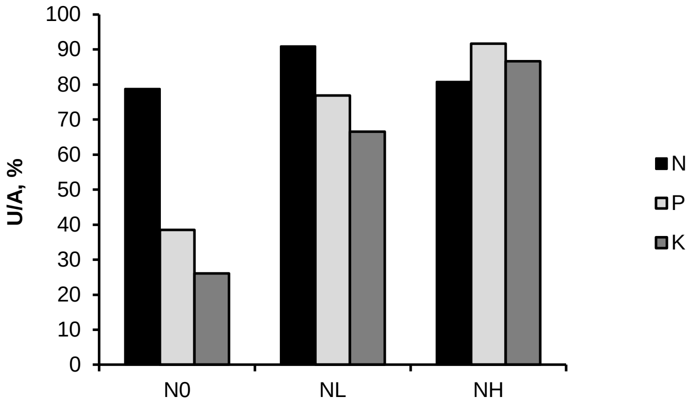


**Fig. 3.5.** Uptake efficiency (actual uptake/available amount) of N, P and K in relation to the level of fertilizer N application (N0, NL, NH), averaged across the data of spring-barley 1994 and 1998, sugar-beets and potatoes (See Appendix 3, Table A.3.1).

More troublesome than the estimation of AN from observed maximum values of UN was the estimation of AP and AK in soil and input from observed maximum values of UP and UK, because shortage of N limited the uptake of P and K. Notwithstanding the difficulties met in estimating AP and AK in P and K input, the procedures applied in Section 3.3.8 were more justified than simply adding the total quantity of fertilizer nutrients to the available nutrient supply in the soil (Chikowo et al., 2010). The pictures of uptake efficiencies, calculated as the ratio of actual uptake to available amount of nutrients (Figure 3.5; Appendix 3, Table A.3.1), demonstrated that, at the absence of N input, only small portions of soil available P and K were taken up, implying that larger portions remained unused. Taking into account that SAP and SAK likely were underestimated, the real uptake efficiencies of AP and AK at N0 must have been even smaller than shown in Figure 3.5.

### *3.4.3. Nitrogen uptake*

Soil available N (SAN in Table 3.11) was greatest for sugar-beets. It was low (24 and 31 kg $ha^{-1}$) in 1994 (spring-barley) and 1995 (potatoes), the two years with the highest winter rainfall (418 and 478 mm, respectively) during the entire period of the long-term trial (Chapter 2, Table 2.3). The availability fraction of fertilizer N ($AF_{IN}$ in Table 3.11) was around 100% for spring-barley 1998 and sugar-beets, and 70 and 86% for spring-barley 1994 and potatoes, the two crops grown in the high winter rainfall years. The lower $AF_{IN}$ in these years may have been a consequence of leaching and denitrification of a part of the added nitrate since at the time of fertilizer application the soil was still wet and partly anaerobic (the fertilizer was $Ca(NO_3)_2$). Almost complete recoveries of fertilizer N were found in other studies in Flevoland soils as well (e.g. Lantinga et al., 2013). Apparently, upward movement of soil moisture during the growing season when evaporation exceeded rainfall, kept the dissolved nutrients ready for uptake.

### *3.4.4. Changes in soil available phosphorus and potassium*

To examine whether soil supplies of available nutrients are changing over time, it is essential to contrast maximum nutrient uptakes by a same crop at different times. In the present study, this was only possible for spring-barley, by comparing the years 1994 and 1998. Figure 3.6 combines the lines of UP at P0 of Figure 3.3 and of UK at K0 of Figure 3.4. It shows that at a given UN, UK at K0 by spring-barley was greater in 1994 than in 1998, but UP at P0 did not differ between these years, at least not as long as UN was less than 85 kg ha$^{-1}$. For instance, at an UN of 80 kg ha$^{-1}$, UK was about 120 in 1994 and 80 kg ha$^{-1}$ in 1998, while UP was about 21 kg ha$^{-1}$ in both years. From extrapolation of the regression lines of P0 (Figure 3.3), however, it was derived that maximum P uptake from the soil alone was about 45 kg ha$^{-1}$ requiring an UN of 267 kg ha$^{-1}$ in 1994, and 25 kg ha$^{-1}$ at an UN of 103 kg ha$^{-1}$ in 1998 (Table 3.7). Although the estimated values of $UN_m$ and $UP_m$ in 1994 must be considered unrealistic since an UN of 267 kg ha$^{-1}$ was outside the range of observed UNs, it probably is justified to conclude that the data point at a decline rather than at a constant level of soil available P between 1994 and 1998.

No maximum uptake of K from the soil alone (SAK) could be established for 1994, because the uptake of K at K0 was almost linearly related to UN (Figure 3.4 and 3.6). In 1998, the maximum uptake of K from the soil alone was reached at an UN of 158 kg ha$^{-1}$ and amounted to 130 kg ha$^{-1}$ (Table 3.10), which is certainly less than in 1994 where at a same UN of 158 kg ha$^{-1}$ the calculated UK would have been 317 kg ha$^{-1}$.

These differences in SAP and SAK between the spring-barley years of 1994 and 1998, corresponded with the hypotheses of gradually diminishing soil fertility. Nevertheless, yields (Table 3.2) were higher in 1998 than in 1994, showing that P or K availabilities were not (yet) production limiting in 1998. Low yield in 1994 was ascribed to poor weather conditions.

It makes less sense to compare SAPs and SAKs in the other two years, because potatoes, the crop in 1995, are known as weak nutrient absorbers, and sugar-beets, the crop in 1999, are known as strong absorbers of N, P and K. Therefore it was considered more realistic to compare UP and UK at a same UN of the crops. At an UN of 200 kg ha$^{-1}$, UP from the soil alone was 23.3 kg ha$^{-1}$ by potatoes in 1995, and 21.9 kg ha$^{-1}$ by sugar-beets in 1999. The data for UK were 201 and 332 kg ha$^{-1}$, respectively. This certainly did not point to a decline of soil available K. The relatively low UP by sugar-beets (Figure 3.3) was caused by low P mass fractions. Therefore, it remained uncertain whether SAP decreased from 1995 to 1999.

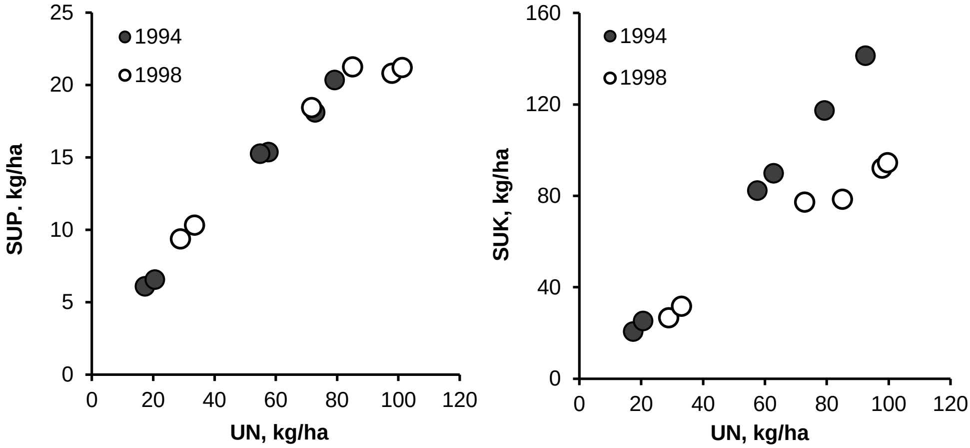


**Fig. 3.6**. Soil P uptake (SUP) (left-hand graph), and soil K uptake (SUK) (right-hand graph) by spring-barley in 1994 and 1998 in relation to UN.

*3.4.5. Nitrogen and phosphorus interactions*

Sugar-beets seemed to take up more P from the soil alone than spring-barley and especially potatoes did (Table 3.6), but the differences in UP among the crops were affected by the large differences in UN among the crops. The four crops had only a limited overlap in UN, roughly from 60 to 90 kg $ha^{-1}$. At these UN values, uptakes of P from the soil alone were in proportions of about 100 : 80 : 50 for spring-barley, sugar-beets, and potatoes, respectively. The maximum values of ΔUPs (*i.e.* $UP_m$ at (P1 – P0) in Table 3.7) were 6.4, 18.3, and 7.3 kg $ha^{-1}$ and corresponded to rounded recovery fractions of 26, 28 and 8% of the respective P inputs for spring-barley, sugar-beets and potatoes. The maximum values of ΔAPs (*i.e.* Available (P1 – P0) in Table 3.6) were 7.0, 5.4, 15.3, and 5.3 kg $ha^{-1}$ and corresponded to rounded availability fractions of 28, 21, 24 and 6% of the respective P inputs for spring-barley 1994, spring-barley 1998, sugar-beets and potatoes, respectively. However uncertain some of these calculations may be, the much lower P recovery by potatoes than by spring-barley and sugar-beets is not uncommon (Syers et al., 2008), and it is a major reason why recommended fertilizer P rates, at equal soil P status, are higher for potatoes than for other crops (Table 2.2; Van Dijk & Van Geel, 2010). The maximum $UP_m$s at (P1-P0) in Table 3.7 were reached at $UN_m$ values within the observed UN ranges, except for spring-barley 1998, where UP at (P1 – P0) has no maximum (Figure 3.3). In 1998, the uptake of P from the soil alone reached a maximum of 24.5 kg at $UN_{opt}$ of 103 kg $ha^{-1}$ (Table 3.7) but in the other years, no optimum UN for maximum uptake of P at P0 could be calculated, as explained in the footnotes of Table 3.7. It is again illustrating that soil P was not seriously deficient in this experiment. Nevertheless, in neighbouring Northeast Polder with soils that are on average more sandy than the one used in the present study, but have comparable or even higher soil P, farmers still applied P via chemical fertilizers as well via manure. These farmers' management decisions were ascribed to low confidence in the diagnostic value of P-water, as well as to risk-avoiding strategy (Reijneveld & Oenema, 2012).

*3.4.6. Nitrogen and potassium interactions*

The differences in K uptake among the crops were very large (Table 3.9). Maximum UKs from the soil alone were at least 141, 94, 359 and 209 kg K per ha per season for spring-barley 1994, spring-barley 1998, sugar-beets and potatoes, respectively, according to the K0-regression lines in Figure 3.4. The uptake of K from the soil alone would have been even more if more N had been applied.

The differences in UK from the soil alone among the crops were affected by the large differences in UN, similar to the situation for UP. For the common range of UN values between 60 and 90 kg ha$^{-1}$, uptakes of K from the soil alone were in proportions of about 100 : 62 : 78 : 45 for sugar-beets, potatoes, spring-barley 1994 and spring-barley 1998, respectively. The spring-barley data point also here to a decrease in soil available K between 1994 and 1998, as discussed in Section 3.4.4.

Wheat requires similar quantities of N and $K_2O$ (Kemmler, 1983), implying an UK/UN ratio of 0.83; in the present experiment, however, the ratio UK/UN (at NL and NH) in spring-barley varied between 0.9 and 1.7, pointing to an higher K uptake than generally found for wheat and likely also for other cereal crops.

Sugar and starch producing crops are known to require relatively more K than cereal crops, as showed up also in this experiment. In potatoes, UK/UN at K0 varied at NL and at NH between 0.97 and 1.13 and in sugar-beets between 1.25 and 1.9, but it was much higher at N0: 2.3-3.4 and 2.2 – 2.4, respectively.

## 3.5. Conclusions

The soil used in this long-term experiment supplied small amounts of available N, large quantities of available P and huge quantities of available K. N applications in this experiment were too low for realistic estimates of soil available P and K. Uptake efficiencies at N0 were very high for N, and low for P and K. When no N was applied, major parts of soil available P and K could not be used by the crops. Only for potatoes, application of P and K had noticeable effects on yields. Sugar-beets and spring-barley showed none to small yield responses to P and none to K. All crops, however, took up large fractions of applied P and K if N was applied.

After more than 40 years of cultivation, no shortage of P and K was observed for spring-barley and sugar-beets. It implies that crops can be grown in a rotation of e.g. four crops for still a great, yet unknown number of years, even if P and K are only applied to potatoes.

# Appendix 3.

**Table A.3.1**.
Uptake, supplies of available N, P and K from soil and input in kg ha$^{-1}$ and uptake efficiency (UE = actual uptake/available supply) at the individual treatments. The most balanced situation is discussed in Section 4.3.6.

| Treatment | Uptake, kg ha$^{-1}$ | | | Available, kg ha$^{-1}$ | | | Uptake/available, % | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | N | P | K | N | P | K |
| | ***Spring-barley 1994*** | | | | | | | | |
| N0P0K0 | 17.4 | 6.1 | 20.7 | 24 | 20 | 141 | 73 | 30 | 15 |
| N0P0K1 | 20.6 | 6.6 | 25.5 | 24 | 20 | 146 | 86 | 33 | 17 |
| N0P1K0 | 20.6 | 7.7 | 25.3 | 24 | 27 | 141 | 86 | 28 | 18 |
| N0P1K1 | 23.8 | 8.3 | 27.5 | 24 | 27 | 146 | 99 | 30 | 19 |
| NLP0K0 | 57.6 | 15.4 | 82.3 | 65 | 20 | 141 | 89 | 76 | 58 |
| NLP0K1 | 54.9 | 15.3 | 83.4 | 65 | 20 | 146 | 84 | 75 | 57 |
| NLP1K0 | 62.8 | 22.0 | 89.8 | 65 | 27 | 141 | 97 | 81 | 63 |
| NLP1K1 | 63.0 | 21.3 | 92.7 | 65 | 27 | 146 | 97 | 78 | 63 |
| NHP0K0 | 79.2 | 20.3 | 117.4 | 106 | 20 | 141 | 75 | 100 | 83 |
| NHP0K1 | 72.9 | 18.1 | 125.9 | 106 | 20 | 146 | 69 | 89 | 86 |
| NHP1K0 | 92.5 | 27.8 | 141.3 | 106 | 27 | 141 | 87 | 102 | 100 |
| NHP1K1 | 77.4 | 23.5 | 143.0 | 106 | 27 | 146 | 73 | 86 | 98 |
| | | | | **Most balanced NH** | | | **76** | **94** | **92** |
| | ***Spring-barley 1998*** | | | | | | | | |
| N0P0K0 | 29.0 | 9.4 | 26.6 | 44 | 22.1 | 97 | 66 | 43 | 28 |
| N0P0K1 | 33.6 | 10.3 | 34.5 | 44 | 22.1 | 125 | 76 | 47 | 28 |
| N0P1K0 | 33.0 | 11.2 | 31.8 | 44 | 27.4 | 97 | 75 | 41 | 33 |
| N0P1K1 | 26.7 | 8.9 | 28.9 | 44 | 27.4 | 125 | 61 | 32 | 23 |
| NLP0K0 | 85.1 | 21.2 | 78.5 | 84 | 22.1 | 97 | 101 | 96 | 81 |
| NLP0K1 | 71.7 | 18.4 | 86.8 | 84 | 22.1 | 125 | 85 | 83 | 69 |
| NLP1K0 | 72.9 | 22.6 | 77.2 | 84 | 27.4 | 97 | 87 | 82 | 80 |
| NLP1K1 | 77.5 | 23.2 | 91.0 | 84 | 27.4 | 125 | 92 | 85 | 73 |
| NHP0K0 | 97.9 | 20.8 | 92.1 | 124 | 22.1 | 97 | 79 | 94 | 95 |
| NHP0K1 | 101.3 | 21.2 | 113.4 | 124 | 22.1 | 125 | 82 | 96 | 91 |
| NHP1K0 | 99.6 | 24.3 | 94.5 | 124 | 27.4 | 97 | 80 | 89 | 98 |
| NHP1K1 | 106.1 | 27.9 | 122.5 | 124 | 27.4 | 125 | 86 | 102 | 98 |
| | | | | **Most balanced NH** | | | **82** | **95** | **95** |
| | ***Sugar-beets 1999*** | | | | | | | | |
| N0P0K0 | 58.3 | 16.1 | 137.0 | 80 | 29 | 450 | 73 | 55 | 30 |
| N0P0K1 | 69.8 | 18.3 | 177.6 | 80 | 29 | 491 | 87 | 63 | 36 |
| N0P1K0 | 80.8 | 23.6 | 180.9 | 80 | 44 | 450 | 101 | 53 | 40 |
| N0P1K1 | 58.7 | 19.5 | 160.5 | 80 | 44 | 491 | 73 | 44 | 33 |
| NLP0K0 | 165.5 | 17.5 | 294.5 | 179 | 29 | 450 | 92 | 60 | 65 |
| NLP0K1 | 148.6 | 15.3 | 323.2 | 179 | 29 | 491 | 83 | 67 | 66 |
| NLP1K0 | 178.8 | 36.5 | 315.0 | 179 | 44 | 450 | 100 | 82 | 70 |
| NLP1K1 | 162.1 | 35.7 | 339.5 | 179 | 44 | 491 | 91 | 80 | 69 |
| NHP0K0 | 279.9 | 27.7 | 461.0 | 278 | 29 | 450 | 101 | 95 | 102 |
| NHP0K1 | 301.6 | 26.5 | 503.5 | 278 | 29 | 491 | 108 | 91 | 103 |
| NHP1K0 | 243.6 | 43.2 | 359.4 | 278 | 44 | 450 | 88 | 97 | 80 |
| NHP1K1 | 284.9 | 42.5 | 455.1 | 278 | 44 | 491 | 102 | 96 | 93 |
| | | | | **Most balanced NH** | | | **100** | **95** | **95** |

| Treatment | Uptake, kg ha $^{-1}$ | | | Available, kg ha $^{-1}$ | | | Uptake/available, % | | |
|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | N | P | K | N | P | K |
| | ***Potatoes 1995*** | | | | | | | | |
| N0P0K0 | 16.8 | 5.3 | 48.2 | 31 | 23 | 218 | 54 | 23 | 22 |
| N0P0K1 | 20.8 | 7.0 | 60.2 | 31 | 23 | 259 | 67 | 31 | 23 |
| N0P1K0 | 27.6 | 11.3 | 75.3 | 31 | 28 | 218 | 89 | 40 | 35 |
| N0P1K1 | 29.5 | 12.9 | 88.1 | 31 | 28 | 259 | 95 | 46 | 34 |
| NLP0K0 | 136.4 | 17.6 | 150.8 | 168 | 23 | 218 | 81 | 77 | 69 |
| NLP0K1 | 137.2 | 17.1 | 172.8 | 168 | 23 | 259 | 82 | 75 | 67 |
| NLP1K0 | 163.1 | 25.9 | 172.6 | 168 | 28 | 218 | 97 | 92 | 79 |
| NLP1K1 | 162.0 | 24.7 | 204.7 | 168 | 28 | 259 | 96 | 88 | 79 |
| NHP0K0 | 196.1 | 23.4 | 209.1 | 305 | 23 | 218 | 64 | 102 | 96 |
| NHP0K1 | 167.4 | 19.2 | 206.9 | 305 | 23 | 259 | 55 | 84 | 80 |
| NHP1K0 | 210.0 | 27.3 | 203.2 | 305 | 28 | 218 | 69 | 97 | 93 |
| NHP1K1 | 228.6 | 27.9 | 266.4 | 305 | 28 | 259 | 75 | 99 | 103 |
| | | | | **Most balanced NL** | | | **89** | **83** | **74** |

*A.3.1. Dissection of the P uptake response to P input (IP) into an indirect effect and a direct effect*

The response of UP to P input consists of an indirect effect of P caused by increased UN and denoted below by ∆UP (UN), and a direct effect caused by the difference between P1 and P0 at equal uptakes of N, denoted by ∆UP (P1-P0). The total difference between P0 and P1 is denoted by ∆UP (total). All data in kg ha $^{-1}$.

The example refers to spring-barley 1994, treatments NLP0 and NLP1, with N uptakes (UN) of 56.2 and 62.9 kg ha $^{-1}$, respectively (averages across K0 and K1 in Table 3.3). For these values of UN, P uptake (UP) was calculated with polynomial regression equations of the shape $y = a \cdot UN^2 + b \cdot UN + c$, presented in the footnote. Between UNs of 56.2 and 62.9 kg ha $^{-1}$, calculated UPs at P0 differ by 1.65 (19.40-17.75), and calculated UPs at P1 by 2.11 (25.08-22.96). At an UN of 56.2, the difference in calculated UP between P1 and P0 is 5.22 (= 22.96 – 17.75), and at an UN of 62.9 the difference in calculated UP between P1 and P0 is 5.68 (= 25.08 – 19.40). The total difference in yield caused by P application is 7.33 (= 25.08 – 17.75 in bold, or 1.65 + 5.68, or 2.11 +5.22).

| Treatment | At UN of | UP | ∆UP (UN) | ∆UP (P1-P0) | ∆UP (total) |
|---|---|---|---|---|---|
| NLP0 | 56.2[a] | **17.75**[c] | | | |
| | 62.9[b] | 19.40[c] | 1.65 | | |
| NLP1 | 56.2[a] | 22.96[d] | | 5.22 | |
| | 62.9[b] | **25.08**[d] | 2.11 | 5.68 | 7.33 |

[a] Measured UN of treatment NLP0, averaged across K0 and K1 in Table A.3.1.
[b] Measured UN of treatment NLP1, averaged across K0 and K1 in Table A.3.1.
[c] Calculated with $UP = -0.0005 \cdot UN^2 + 0.2726 \cdot UN + 1.3664$ (Figure 3.3)
[d] Calculated with $UP = -0.0016 \cdot UN^2 + 0.4633 \cdot UN - 1.4264$ (Figure 3.3)

# Chapter 4

# Balanced supplies of available N, P and K provided maximum nutrient use efficiencies

## Abstract

The main objectives of this last but one chapter on a 28 years field experiment (1975 through 2002) were to appraise balances among N, P and K in crops and in the supplies from soil and input. For that purpose, assessments were made of physiological use efficiencies (PhE) of N, P and K taken up by the crops, and of agronomic use efficiencies (AE) of available N, P and K supplied by soil and input. The resulting PhE and AE were applied in a framework for the calculation of the quantities of available N, P and K - in balanced proportions - that are required for specified target yields.

Compared with maximum and minimum values from literature, the PhE values of N observed in the experiment were close to maximum, pointing to severe N limitation, but those of P and K were between medium and minimum, especially for spring-barley and sugar-beets. Potato was the only crop effectively using absorbed fertilizer P and K for extra yield.

Medium PhE values of N, P and K derived from literature data were used for the calculation of crop nutrient equivalents (CNE). A (k)CNE of any nutrient was defined as the quantity of the nutrient that, under conditions of balanced nutrition, has the same effect on yield as 1 (k)g of nitrogen. The quantities of N, P and K can be added up when they are expressed in units of CNE, and PhEΣU and AEΣA standing for PhE of the sum of N, P and K taken up, and AE of the sum of available N, P and K, respectively, can be estimated. The percentage fractions of their sum can be calculated as well, facilitating the appraisal of the balance among N, P and K. At perfect balance the fractions of N, P and K are equal, *i.e.* each 33.3%.

Soil supplies of available N, P and K were far from balanced, with average fractions of 8, 40 and 52%, respectively, of the sum of soil available N, P and K (ΣSA).
Best balances of the supplies of available N, P and K from soil and input together were found at high inputs of N and no applications of P and K in the case of sugar-beets and spring-barley, and at medium inputs of N in combination with P and especially K application in the case of potatoes. At these NPK inputs, the relative

agronomic use efficiency of the sum of available N, P and K (RAEΣA) was 90% of the theoretically maximum value of AEΣA.
Calculations revealed that spring-barley and sugar-beets needed only input of N (about 200 and 125 kg $ha^{-1}$) to attain water-limited grain yields of 8.5 Mg $ha^{-1}$ and root dry-matter yields of 15 Mg $ha^{-1}$, respectively. Potatoes required smaller than the standard inputs of N, and larger than the standard inputs of P and K for the water-limited tuber dry-matter production of 15 Mg $ha^{-1}$. In a rotation with cereals, sugar-beets and potatoes, application of P and K to potatoes only would suffice to continue cropping for another great, yet unknown number of years.

## Highlights

- The quantities of N, P and K were expressed in units of crop nutrient equivalents (CNE), where one (k)CNE was defined as the quantity of the nutrient that, under conditions of balanced nutrition, has the same effect on yield as 1 (k)g of nitrogen.
- The concept of CNE greatly facilitated the appraisal of the balances among N, P and K in crops and in supply by soil and input.
- In the long-term experiment on the former sea bottom, soil available N, P and K were on average 8, 40 and 52% of their sum ($\Sigma SA_{kCNE}$), so far from the balance of 33, 33 and 33%
- The best balances of available N, P and K from soil and inputs together were obtained at large inputs of N and no inputs of P and K in the cases of spring-barley and sugar-beets, and at medium N and larger than the standard recommendations for P and K input in the case of potatoes.
- Compared to literature data, N was maximum diluted in all crops if there was no N input, while P and K tended to accumulate in the crops.

**Key words:** agronomic nutrient use efficiency (AE), crop nutrient equivalent (CNE), physiological nutrient use efficiency (PhE), relative agronomic use efficiency of the sum of available N, P and K (RAEΣA)

## 4.1. Introduction

This is the last but one chapter on a long-term study of changes in nutrient supplies to crops on a reclaimed former sea bottom. The basic questions were how long it would take before crop performance suffers from shortages in N, P and K, and whether different crops behave and respond similarly to applied nutrients. The experiment ran at the ‘Ir, A.P. Minderhoudhoeve’ (APM), an experimental farm near

Swifterbant in the polder Oostelijk (Eastern) Flevoland, the Netherlands.

Chapter 1 was a short introduction to the history of the reclamation of the former sea and the development of the Flevo-polders. Chapter 2 reported on the yields during the long-term experiment running from 1975 through 2002, comprising 28 cropping seasons. No response to K was found, a highly significant response to N, and irregular responses to P for sugar-beets, potatoes and spring-barley, but never for silage maize and winter-wheat. Yields on unfertilized soil, adjusted to average winter rainfall, did not significantly change during the 28 years period.

The third chapter dealt with the period (1994-1999) in which crops were chemically analysed allowing the assessment of nutrient uptake. Its main objective was to determine availability, uptake and uptake efficiency of available N, P and K, to get a better understanding of the crop performance described in Chapter 2. The supplies of soil available N were small, and those of available P and K very large to seemingly infinite. Consequently, uptake efficiencies of P and K were low, implying that large portions of available soil P and soil K were not used by the crops when no N was applied.

The main objective of the present chapter is, using the results of Chapters 2 and 3 and applying some concepts that have been developed in soil fertility research in tropical regions, to assess the balance or equilibrium among N, P and K in nutrient supply and uptake. Although going beyond the basic questions of the long-term experiment, the study considerably deepens the insights in the performance of crops in relation to the supply of nutrients. First, the physiological and agronomic use efficiencies (PhE and AE) are assessed and compared with maximum and minimum values as derived from literature data. The relationships attained and the insights resulting from this chapter as well as from Chapter 2 and Chapter 3 are applied to build a framework for the assessment of balanced supplies of available N, P and K needed for specified target yields. Water-limited crop production is aimed at, and balanced N, P and K supplies are strived for, as such a balance facilitates simultaneous optimization of environmental and financial goals (Janssen et al., 1994).  when NPK supplies are balanced, the use efficiency of available NPK from soil and input together is at its maximum and nutrient losses to the environment are minimum.

Basic information in this chapter starts with data on nutrient mass fractions as found in literature. They are used to calculate maximum and minimum physiological nutrient use efficiency (PhE), and crop nutrient equivalents (CNE). As the concepts of PhE and CNE were introduced earlier (Janssen, 1998; 2011), they receive only a short explanation in the main text of this article, while in Appendix 4 some theoretical support is offered. The physiological nutrient use efficiencies at 'Ir. A.P. Minderhoudhoeve' (henceforth denoted by APM) are compared with the extreme values found in literature to assess relative physiological nutrient use efficiencies (RPhE) to appraise crop nutrient status (Sections 4.3.2 – 4.3.6). Available N, P and K are calculated as fractions of their CNE sum and it will be shown that equal fractions of available N, P and K are optimum for maximum nutrient use efficiency. Crop independent indices are formulated to appraise the use efficiencies of the sum of N, P and K. The experimental results and developed relationships are combined to assemble balanced supplies from soil and input of available N, P and K, required for the target of water-limited crop production.

## 4.2. Materials and methods

*4.2.1. Soil, experimental layout and crop sampling*

The soils of the Minderhoudhoeve belong to the mapping unit Mn35A. They were classified as calcareous Entisols ('kalkrijke poldervaaggronden') with a texture of loam to clay loam (25-35% clay), and evaluated as very fertile and very suitable for arable crops (Eilander et al., 1990). Some chemical data were given in Table 2.2 of Chapter 2. The experimental design was a 3 N · $2^2$ PK factorial with two replicates, during the period discussed in the present chapter and in Chapter 3 (1994-1999). N was applied at 0, 67 and 133% of the standard recommended rate (100%) as based on soil mineral N. Further details were presented in Chapter 3.

*4.2.2. Nutrient mass fractions (MF) and Physiological nutrient use efficiency (PhE)*

Maximum and minimum values of mass fractions (MF, g $kg^{-1}$) of N, P and K were derived from chemical analysis of crop components at APM, and from a review on nutrient mass fractions data (Nijhof, 1987). The ratio of yield of the economically interesting plant parts (Y) to uptake by the whole crop (U) was coded as PhE, 'physiological nutrient use efficiency' (Harmsen, 2003; Janssen, 2011)

$$PhE = Y/U \qquad \text{(Eq. 4.1)}$$

Y and U usually are expressed in the same units, e.g. kg $ha^{-1}$, and hence PhE in kg $kg^{-1}$. Physiological efficiency occasionally is named conversion efficiency (Chikowo et al., 2010), but more often internal utilization efficiency (Witt et al., 1999). Indicating the dry mass of the economically interesting parts (roots of sugar-beets, grains of spring-barley) by yield (Y), and that of the remaining crop parts (foliage of sugar-beets, straw of spring-barley) by 'stover' (S), the uptake by the whole crop was calculated as:

$$U = (Y \cdot MF_y + S \cdot MF_s)/1000 \quad \text{(Eq. 4.2)}$$

MF is mass fraction in g $kg^{-1}$, and the sub-scripts y and s in Equation 4.2 stand for yield and stover. The ratio of the dry mass of the yield to the dry biomass (B) of the total crop is the harvest index (HI), so Y = HI · B, and S = (1-HI) · B. Hence, Equation 4.2 can be rewritten as:

$$U = [HI \cdot B \cdot MF_y + (1 - HI) \cdot B \cdot MF_s]/1000 \quad \text{(Eq. 4.3)}$$

U and B are expressed in kg $ha^{-1}$ and MF in g $kg^{-1}$. Substitution of Y = HI · B and of Equation 4.3 in Equation 4.1 results in:

$$PhE = (HI \cdot B)/[(HI \cdot B \cdot MF_y + (1 - HI) \cdot B \cdot MF_s)]/1000$$
$$PhE = 1000 \cdot (HI)/(HI \cdot MF_y + (1 - HI) \cdot MF_s) \quad \text{(Eq. 4.4)}$$

From Equation 4.4 it follows that PhE increases with increasing HI. It is obvious that PhE is greater at low than at high MF values. At a given HI, PhE is highest ($PhE_{max}$) when the nutrient is maximally diluted in the crop, so when MF is minimum ($MF_{min}$), and lowest ($PhE_{min}$) when the nutrient is maximally accumulated, so when MF is maximum ($MF_{max}$) (Janssen, 2011). Both situations, maximum and minimum PhE, represent unbalanced plant nutrition, where one nutrient (*e.g.* N) is strongly growth limiting and one or both other nutrients (P and K) are at unnecessarily high levels, or vice versa. Balanced nutrition of N, P and K is obtained when PhE of each of the three is (close to) $PhE_{med}$, standing for medium values of PhE, in the middle between the two extremes (see QUEFTS principles in Appendix 4).

So, maximum, minimum and medium values of PhE were calculated as:

$$PhE_{max} = 1000 \cdot (HI)/(HI \cdot MF_{y,\,min} + (1 - HI) \cdot MF_{s,\,min})) \quad \text{(Eq. 4.5)}$$
$$PhE_{min} = 1000 \cdot (HI)/(HI \cdot MF_{y,\,max} + (1 - HI) \cdot MF_{s,\,max})) \quad \text{(Eq. 4.6)}$$
$$PhE_{med} = 0.5 \cdot (PhE_{max} + PhE_{min}) = m \quad \text{(Eq. 4.7)}$$

Under optimum growth conditions, HI is practically constant, and so are $PhE_{max}$ and $PhE_{min}$. In that situation, two straight lines can be drawn in graphs of yield (Y) versus uptake (U), with Y = U · PhE. The upper line represents, in the symbols used by Sattari et al. (2014), $Y_i^d$, yield at maximum dilution (*d*) of nutrient *i*, the lower line stands for $Y_i^a$, yield at maximum accumulation (*a*) of nutrient *i*. $Y_i^d$ and $Y_i^a$ are basic concepts of the model QUEFTS (Appendix 4; Janssen et al., 1990). Under sub-optimum conditions, HI may alter upon input of nutrients. Consequently, $PhE_{max}$ and $PhE_{min}$ change, often differently for N, P, and K. Because no data on HI and $MF_s$ for ***potatoes*** were available in this study, Equations 4.5 and 4.6 could not directly be applied to this crop. Instead, use was made of relationships presented in a report on the application of the model QUEFTS to potatoes (Velthof & Van Erp 1999), in which yields at maximum dilution (YND) and maximum accumulation of N (YNA) were described by equations such as:

$YND = b_N \cdot (UN - r_N)$ and $YNA = c_N \cdot (UN - r_N)$.

Values of the regression parameters $b_N$, $c_N$ and $r_N$ were determined in experiments, for N, as well as for P and K. Because $r_N$, $r_P$ and $r_K$ were very small, the equations of YND and YNA could be translated into equations with the regression parameters $f_N$ and $g_n$:

$YND = f_N \cdot UN$ and $YNA = g_N \cdot UN$. The medium line is $YN_{med} = m \cdot UN$, where $m = 0.5 \cdot (f + g)$. Denoting the differences $(f - m)$/m and $(m - g)$/m by $e$, standing for extreme, it follows:

$$YND = (1 + e_N) \cdot m_N \cdot UN \quad \text{(Eq. 4.8a)}$$
$$YNA = (1 - e_N) \cdot m_N \cdot UN \quad \text{(Eq. 4.8b)}$$
$$YND/YNA = (1 + e_N)/(1 - e_N) = PhEN_{max}/PhEN_{min} \quad \text{(Eq. 4.8c)}$$

For P and K similar equations as Equations 4.8 for N were used.

*4.2.3. Crop nutrient equivalents, balance among N, P and K*

It is not easy to deal with the equilibrium or balance among N, P and K when their quantities are expressed in mass units such as kilograms (kg), because one kg of N has another effect on yield than one kg of P, or one kg of K. To facilitate quantitative comparison of N, P and K, it was proposed (Janssen 1998, 2011, Ezui et al., 2016) to express the quantities of N, P and K in crop nutrient equivalents (CNE), using conversion factors CFP and CFK. The procedure to calculate CFP and CFK is explained in Appendix 4, Equations A.4.1a and A.4.1b.

Expressed in kCNE, the quantities of N, P and K are tot up, and FN, FP and FK represent the percentage fractions of N, P and K in their kCNE sum ($\Sigma_{kCNE}$).

The supplies of available nutrients by soil (SA) or input (IA) were estimated as the maximum crop uptakes of the nutrient from soil or input (Chapter 3). The sum of available N, P, and K from soil (ΣSA) and from input (ΣIA) together, denoted by

ΣA:

$\Sigma A_{kCNE} = \Sigma SA_{kCNE} + \Sigma IA_{kCNE}$; and

$$\Sigma A_{kCNE} = SAN_{kCNE} + SAP_{kCNE} + SAK_{kCNE} + IAN_{kCNE} + IAP_{kCNE} + IAK_{kCNE} \quad \text{(Eq. 4.9)}$$

Balanced nutrition is obtained when the soil (SA) plus input (IA) supplies of available N, P and K, expressed in kCNE, are equal (Janssen 1998, 2011):

$SAN_{kCNE} + IAN_{kCNE} = SAP_{kCNE} + IAP_{kCNE} = SAK_{kCNE} + IAK_{kCNE}$ or
$\Sigma AN_{kCNE} = \Sigma SAP_{kCNE} = \Sigma AK_{kCNE}$ (Eq. 4.10a)
$\Sigma AN_{kCNE}/\Sigma A_{kCNE} = \Sigma AP_{kCNE}/\Sigma A_{kCNE}) = \Sigma AK_{kCNE}/\Sigma A_{kCNE;}$ or (Eq. 4.10b)
$FN = FP = FK = 33.3\%$ of $\Sigma A_{kCNE}$ (Eq. 4.10c)

In unbalanced situations, FN, FP and FK are not equal, but their average is of course 33.3%.
Therefore, the standard deviation of FN, FP and FK was used as a measure for the state of equilibrium or balance among N, P and K; it was denoted as (SD FΣA) for the supplies of available N, P and K, and as (SD FΣU) for the uptakes of N, P and K. It is obvious that SD FΣA and SD FΣU are zero at perfectly balanced supplies of available N, P and K and perfectly balanced uptakes of N, P and K, respectively.

*4.2.4. Agronomic nutrient use efficiency (AE)*
Another concept used in this chapter is 'agronomic nutrient use efficiency' (AE). It is the relation of yield to the amount of available nutrient (Y/A). When AE refers to the sum of available N, P and K, it is denoted by AEΣA, and relates yield to $\Sigma A_{kCNE}$. It is the product of uptake efficiency, being the ratio of actual uptake to available supply as discussed in Chapter 3, ($UE = \Sigma U_{kCNE}/\Sigma A_{kCNE}$) and physiological efficiency ($PhE = Y/\Sigma U_{kCNE}$), so:

$$AE\Sigma A_{kCNE} = \Sigma U_{kCNE}/\Sigma A_{kCNE} \cdot Y/\Sigma U_{kCNE} = Y/\Sigma A_{kCNE} \quad \text{(Eq. 4.11a)}$$

The (very near to) maximum value of $AE\Sigma A_{kCNE}$ is found at balanced supplies of available N, P and K. If under those conditions the available nutrients would entirely be taken up, so if $\Sigma U_{kCNE}/\Sigma A_{kCNE} = 1$, $AE\Sigma A_{kCNE}$ would equal $Y/\Sigma U_{kCNE}$. Because $\Sigma U_{kCNE} = UN_{kCNE} + UP_{kCNE} + UK_{kCNE}$ and $UN_{kCNE} = UP_{kCNE} = UK_{kCNE}$ it holds in that case:

$$\Sigma U_{kCNE} = 3 \cdot UN_{kCNE} = 3 \cdot UP_{kCNE} = 3 \cdot UK_{kCNE} \quad \text{(Eq. 4.11b)}$$

The theoretical maximum value of $AE\Sigma A_{kCNE}$ (kg $kCNE^{-1}$) is accordingly:

$$AE\Sigma A_{kCNE\ max} = PhEN_{kCNE\ med}/3 = PhEP_{kCNE\ med}/3 = PhEK_{kCNE\ med}/3 \quad \text{(Eq. 4.11c)}$$

*4.2.5. Indices for the appraisal of nutrient use efficiency*
For the comparison of nutrient use efficiency of different crops and/or different nutrients, the relative nutrient use efficiency (RE), can be used. It is expressed as a

percentage of the difference between the maximum ($E_{max}$) and minimum ($E_{min}$) efficiency value:

$$RE\ (\%) = 100 \cdot (E - E_{min})/(E_{max} - E_{min}) \qquad \text{(Eq. 4.12a)}$$

The minimum and maximum values of the *uptake* efficiency (UE= 100 · U/A) are simply: $UE_{min}$ = 0 (no uptake) and $UE_{max}$ =100 (complete uptake of the available supply). It follows from Equations 4.5, 4.6 and 4.7 that the values of RPhE are 100, 0 and 50% for $PhE_{max}$, $PhE_{min}$ and $PhE_{med}$, respectively.
The theoretically maximum value of the *agronomic* efficiency, $AE\Sigma A_{max}$, given in Equation 4.11c, is found when the relative uptake efficiency (RUE) is 100%. The theoretically minimum value of AEΣA is 0, found at RUE is 0%. The 'relative agronomic use efficiency of all available nutrients', denoted by RAEΣA, is then:

$$RAE\Sigma A = 100 \cdot AE\Sigma A_{kCNE}/AE\Sigma A_{kCNE,max} \qquad \text{(Eq. 4.12b)}$$

From Equation 4.11c it follows:

$$RAE\Sigma A = 300 \cdot AE\Sigma A/PhEN_{med} = 300 \cdot AE\Sigma A/PhEP_{kCNE\ med}$$
$$= 300 \cdot AE\Sigma A/PhEK_{kCNE\ med} \qquad \text{(Eq. 4.12c)}$$

Also, the maximum value of the *physiological* efficiency of the sum of N, P and K taken up ($PhE\Sigma U_{kCNE,max}$), is found at or near balanced uptakes of N, P and K (Appendix 4, Section A.4.2 and A.4.4), and hence can be described by:

$$PhE\Sigma U_{kCNE,max} = PhEN_{med}/3 = PhEP_{kCNE,med}/3 = PhEK_{kCNE,med}/3 \qquad \text{(Eq. 4.12d)}$$

Theoretically, the minimum value of physiological efficiency of the sum of N, P and K taken up (PhEΣU) would be attained when all three nutrients, N, P and K are maximally accumulated in the crop, or at least when the nutrient with the lowest value of U · $PhE_{min}$ is maximally accumulated. Such is possible when other growth conditions of water supply (drought), radiation, temperature, are comparatively (very) poor. In extreme situations, *e.g.* at very low soil fertility, the harvest index may be zero, in which case PhE of each nutrient and hence $PhE\Sigma U_{kCNE,min}$ would be 0. Substitution of $PhE\Sigma U_{kCNE,max}$ and $PhE\Sigma U_{kCNE,min}$ = 0 in Equation 4.12a yields for RPhEΣU, the 'relative physiological efficiency of all absorbed nutrients':

$$RPhE\Sigma U = 100 \cdot PhE\Sigma U_{kCNE}/PhE\Sigma U_{kCNE\ max}$$
$$= 300 \cdot PhE\Sigma U_{kCNE}/PhEN_{med} \qquad \text{(Eq. 4.12e)}$$

Equations 4.12a-e are used in a reverse way to calculate the amounts of available nutrients that are required for a certain target yield with balanced NPK proportions.

From Equation 4.11c it follows that the minimum supply of available N, P and K (minimum $\Sigma A_{min}$) to attain a target yield (YT) is found at maximum agronomic use efficiency:

$$\text{Minimum } \Sigma A_{kCNE} = YT/AE\Sigma A_{kCNE\ max} \qquad \text{(Eq. 4.13a)}$$

In reality, maximum agronomic use efficiency can never be attained and, hence, $AE\Sigma A$ will be less than $AE\Sigma A_{max}$, namely $RAE\Sigma A \cdot AE\Sigma A_{max}$. From Equations 4.12e and 4.13a it follows:

$$\begin{aligned}\text{Minimum } \Sigma A_{kCNE} &= YT/(RAE\Sigma A \cdot AE\Sigma A_{kCNE\ max}) \\ &= 3 \cdot YT/(RAE\Sigma A \cdot PhEN_{med}) \qquad \text{(Eq. 4.13b)}\end{aligned}$$

Combining Equations 4.11a and 4.13b and considering the minimum supply to be the optimum ($\Sigma_{opt}$) for yield and environment it follows:

$$\Sigma_{opt}\ AN_{kCNE} = \Sigma_{opt}\ AP_{kCNE} = \Sigma_{opt}\ AK_{kCNE} = YT/(RAE\Sigma A \cdot PhEN_{med}) \qquad \text{(Eq. 4.13c)}$$

After conversion of kCNE into kg, using Equations A.4.1a and A.4.1b (see Appendix 4) the required or optimum supply of available N, P and K is found by:

$$\Sigma_{opt}\ AN_{kg} = YT/(RAE\Sigma A \cdot PhEN_{med}) \qquad \text{(Eq. 4.13d)}$$
$$\Sigma_{opt}\ AP_{kg} = YT/(RAE\Sigma A \cdot CFP \cdot PhEN_{med}) = YT/(RAE\Sigma A \cdot PhEP_{kg\ med}) \qquad \text{(Eq. 4.13e)}$$
$$\Sigma_{opt}\ AK_{kg} = YT/(RAE\Sigma A \cdot CFK \cdot PhEN_{med}) = YT/(RAE\Sigma A \cdot PhEK_{kg\ med}) \qquad \text{(Eq. 4.13f)}$$

It should be noted that in Equations 4.13def, $\Sigma_{opt}\ AN_{kg}$, $\Sigma_{opt}\ AP_{kg}$ , $\Sigma_{opt}\ AK_{kg}$, and YT are in kg $ha^{-1}$ and $PhEN_{med}$, $PhEP_{med}$ and $PhEK_{med}$ are in kg $kg^{-1}$.

## 4.3. Results

### *4.3.1. Nutrient mass fractions (MF) and physiological nutrient use efficiency (PhE)*

In Table 4.1, minimum and maximum nutrient mass fractions as observed at APM are compared with those reported in literature (Nijhof, 1987). Minimum MFN was lower than in literature, minimum MFP was sometimes lower and sometimes higher than in literature, while minimum MFK was higher except for potato tubers where APM and literature had similar $MFK_{min}$. The observed values reflected a very poor N, a high K and an intermediate P status of the soil at APM, in agreement with conclusions before (Chapters 2 and 3). The ratios of observed maximum to minimum nutrient mass fractions at APM were (much) smaller than similar ratios in the literature.

Interpretation of nutrient mass fractions was problematic for silage maize, because the stage of 'ripeness' of silage maize at sampling was not always mentioned in literature, while MFs change during maize growth. Because of these difficulties average withdrawals of N, P and K per ton silage maize (Van Schooten et al., 2009) were used as basis for comparison (default MF values in Table 4.1), assuming that these values would be somewhere in the middle between maximum and minimum MF. Maximum MFN at APM is close to default MFN, implying that maize N never was really accumulated at APM; $MFN_{min}$ at APM was far below default MFN again illustrating the poor N status in the soil at APM. Default MFP was in the middle between the maximum and minimum MFP at APM, while default MFK was far below maximum and not much above minimum MFK at APM, pointing to a 'standard' P status and a high K status of silage maize at APM.

The maximum and minimum nutrient mass fractions, as found in literature (Table 4.1), were used for the calculation of minimum and maximum physiological efficiencies with Equations 4.5 and 4.6 (Table 4.2). In the case of **sugar-beets**, different values of the harvest index (HI) had to be taken into account because, as a consequence of the greater stimulation of leaf than root production, HI decreased with increasing N application (Table 4.2). The values of $PhEN_{med}$, calculated as the average of $PhEN_{max}$ and $PhEN_{min}$ were between 80 and 93 kg $kg^{-1}$. In the case of **potatoes** PhE was based on information from two literature sources: (i) experimentally established relations between yield and uptake (Velthof & Van Erp, 1999), (ii) the ratio $MF_{max}$ to $MF_{min}$ found for the literature data in Table 4.1. The experimentally established relations between yield and uptake were YND = 0.4 · (UN – 10) and YNA = 0.2 · (UN – 10), where YND and YNA are in tons of fresh tubers (Velthof & Van Erp, 1999). These relations indicated that at least 10 kg N had to be taken up to get any tuber yield. Taking into account a dry-matter fraction of 0.259 and 0.234 at low and high N provision (see Section 2.2.3. in Chapter 2), and neglecting the minimum requirement of 10 kg N, rounded values of YND/UN (= $PhEN_{max}$) and YNA/UN (=$PhEN_{min}$) were found to be 98 and 44; hence $PhE_{med}$ (m in Eq. 4.7 and 4.9) was 71, and YND/YNA was 2.2. From Table 4.1, it follows that $MFN_{max}/MFN_{min}$ in literature was 25/9 = 2.7778, somewhat wider than 2.2 as Velthof & Van Erp found. Because the ratio of N in potato (tubers plus foliage) to N in tubers is supposed to be constant (1.188, Velthof & Van Erp, 1999; about 1.14, Vos 1997), it follows that $PhEN_{max}/PhEN_{min}$ is equal to $MF_{max}/MF_{min}$ in tubers, so it was 2.7778. Hence, according to Equation 4.8c, YND/YNA = $(m_N + e_N)/(m_N – e_N)$ = 2.7778, and assuming that $m$ keeps the value of 71, $e_N$ was calculated to be 33.458, so rounded values of $PhEN_{max}$ and $PhEN_{min}$ were estimated at 105 and 38 kg $kg^{-1}$ (Table 4.2). In a similar way, $PhEP_{max}$ and $PhEP_{min}$ were found to be 814 and 136 kg $kg^{-1}$, while $PhEK_{max}$ and $PhEK_{min}$ were 74 and 17 (Table 4.2).

**Table 4.1**.
Comparison of maximum and minimum values of N, P and K mass fractions (MF, g $kg^{-1}$) as found in analysed crop components at APM and in literature (Nijhof, 1987).

| Crop | Component | | MFN | | MFP | | MFK | |
|---|---|---|---|---|---|---|---|---|
| | | | Max | Min | Max | Min | Max | Min |
| Spring barley | Grain | APM | 16.5 | 11.5 | 4.53 | 3.22 | 5.62 | 4.80 |
| | | Literature | 43.0 | 11.0 | 6.0 | 1.6 | 11.0 | 3.0 |
| | | Average | 29.7 | 11.2 | 5.26 | 2.41 | 8.31 | 3.90 |
| | Straw | APM | 6 | 1.48 | 2.883 | 0.31 | 26.4 | 11 |
| | | Literature | 22 | 3 | 5 | 0.4 | 29 | 7.5 |
| | | Average | 14 | 2.24 | 3.94 | 0.36 | 27.7 | 9.25 |
| Sugar-beets | Roots | APM | 7.2 | 3.8 | 1.6 | 0.7 | 8.9 | 6.8 |
| | | Literature | 13.8 | 5.1 | 1.9 | 0.3 | 13.7 | 4.3 |
| | | Average | 10.5 | 4.4 | 1.8 | 0.5 | 11.3 | 5.5 |
| | Leaves | APM | 24.7 | 14.1 | 3.2 | 1.5 | 49.4 | 36.8 |
| | | Literature | 35.4 | 6.3 | 4 | 0.8 | 80 | 6 |
| | | Average | 30 | 10.2 | 3.6 | 1.2 | 64.7 | 21.4 |
| Potatoes | Tuber | APM | 16.3 | 6.3 | 2.88 | 1.61 | 18.6 | 10.8 |
| | | Literature | 25 | 9 | 6 | 1 | 46 | 11 |
| | | Average | 20.7 | 7.7 | 4.4 | 1.3 | 32.3 | 10.9 |
| Silage maize | Biomass | APM | 13.5 | 3.7 | 3.26 | 0.81 | 28.8 | 8.2 |
| | | Default[a] | 12.4 | | 1.97 | | 13.0 | |

[a] Derived from Van Schooten et al., 2009. See text Section 4.3.1

**Table 4.2**.
Maximum and minimum physiological efficiencies of N, P and K (PhE in kg $kg^{-1}$), as calculated with Equations 4.5 and 4.6, using the minimum and maximum MF values found in Literature (Table 4.1). For sugar-beets a distinction was made according to the harvest index (HI) corresponding with the N application levels. Conversion factors CFP and CFK were calculated as ($PhEN_{max}$ + $PhEN_{min}$)/($PhEP_{max}$ + $PhEP_{min}$) and ($PhEN_{max}$ + $PhEN_{min}$)/($PhEK_{max}$ + $PhEK_{min}$).

| Crop | | PhEN | | PhEP | | | PhEK | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Max | Min | Max | Min | CFP | Max | Min | CFK |
| Spring-barley | | 72 | 16 | 506 | 93 | 0.15 | 99 | 26 | 0.70 |
| Sugar-beets | | 135[b] | 38[b] | 1650[c] | 215[c] | 0.09 | 166[d] | 23[d] | 0.90[e] |
| **IN** | **HI** | | | | | | | | |
| N0 | 0.772 | 144 | 41 | 1865 | 223 | 0.09 | 180 | 27 | 0.89 |
| NL | 0.744 | 138 | 39 | 1742 | 214 | 0.09 | 173 | 24 | 0.90 |
| NH | 0.688 | 126 | 34 | 1511 | 196 | 0.09 | 160 | 20 | 0.89 |
| Potatoes [a] | | 105 | 38 | 814 | 136 | 0.15 | 74 | 17 | 1.55 |

[a] Values of PhE were derived from Velthof & Van Erp (1999) in combination with $PhE_{max}$/$PhE_{min}$ of about 2.8 for N, 6 for P and 4.2 for K. See text Section 4.2.2 and Equations 4.8abc.
[b] Approximate value derived from Figure 4.1.
[c] Approximate value derived from Figure 4.2 at UP = 30.
[d] Approximate value derived from Figure 4.3 at UK = 300.
[e] Although the calculated value was 0.92, for convenience a rounded value of 0.90 was applied for CFK of sugar-beets.

### *4.3.2. PhEN: yields (Y) in relation to uptake of nitrogen (UN)*

In Figure 4.1, relations between yields (Y) and nitrogen uptake (UN) are shown, for spring-barley, sugar-beets and potatoes. The ratio of Y to UN represents the physiological efficiency of N (PhEN) (Equation 4.1). The highest line (N diluted) in Figure 4.1 denotes the yield at maximum dilution: $Y_N^d = U \cdot PhEN_{max}$, and the lowest line stands for $Y_N^a$, yield at maximum accumulation: $Y_N^a = U \cdot PhEN_{min}$. For sugar-beets, the relations between $Y_N^d$ and UN, and between $Y_N^a$ and UN were not precisely linear because its harvest index decreased with increasing UN. The equations were found to be $Y_N^d = -0.0807 \cdot UN^2 + 149.39 \cdot UN$ and $Y_N^a = -0.0344 \cdot UN^2 + 43.592 \cdot UN$, which for the range of observed UNs approximately came down to a $PhEN_{max}$ of 135 and a $PhEN_{min}$ of 38. The ratio of $PhEN_{max}/PhEN_{min}$ was about 4.6 for spring-barley, 3.6 for sugar-beets, and 2.8 for potatoes.

The points shown in Figure 4.1 represent the treatments P1K1, P1K0, P0K1 and P0K0 per N level: N0, NL and NH. Regression coefficients of the polynomial curves and related properties are given in Table 4.3. Because the regression lines of spring-barley 1994 and 1998 were almost equal, also the regression line for the two years combined was calculated (Table 4.3). Optimum UN ($UN_m$) sat within the range of observed UNs for spring-barley 1998, the combined line of spring-barley 1994 and 1998, and for sugar-beets, and the corresponding maximum yields of (about) 6050 and 16329 kg ha$^{-1}$, respectively, were realistic (Table 4.3). As the curve of potatoes hardly levelled off (Figure 4.1) the calculated $UN_m$ of 382 was far beyond the highest observed UN of 229 kg ha$^{-1}$. The points of sugar-beets had the largest deviations around the regression line and hence sugar-beets had the lowest R-squared values in Table 4.3. The relations between observed yields and UN in the graphs of Figure 4.1 clearly show that N was maximally diluted at low UN in all four years.

**Table 4.3**.
Parameters of the polynomial regression equations relating yield to UN (curves in Figure 4.1), calculated $UN_m$ for maximum or minimum yield ($Y_m$). The parameters *a, b* and *c* refer to equations $y = ax^2 + bx + c$, where y is yield and x is UN, both in kg ha$^{-1}$.

| **Crop** | | ***-a*** | ***b*** | ***c*** | **$R^2$** | **$UN_m$** | **$Y_m$** |
|---|---|---|---|---|---|---|---|
| Spring-barley | 1994 | 0.2543 | 101 | -598 | 0.9883 | 198 | 9346 |
| | 1998 | 0.6396 | 136 | -1307 | 0.9845 | 107 | 5968 |
| | both years | 0.5987 | 132 | -1157 | 0.9795 | 110 | 6126 |
| Sugar-beets | | 0.2049 | 109 | 1723 | 0.9188 | 267 | 16329 |
| Potatoes [a] | | 0.0853 | 65 | 1500 | 0.9836 | 382[b] | 13920[b] |

[a] Tubers and foliage; N amounts in potato foliage were calculated as 0.188 times N in potato tuber (Velthof & Van Erp, 1999).
[b] Although calculated values of $UN_m$ were found by extrapolation of the regression equations beyond actual UN, values of $Y_m$ have been calculated for curiosity.

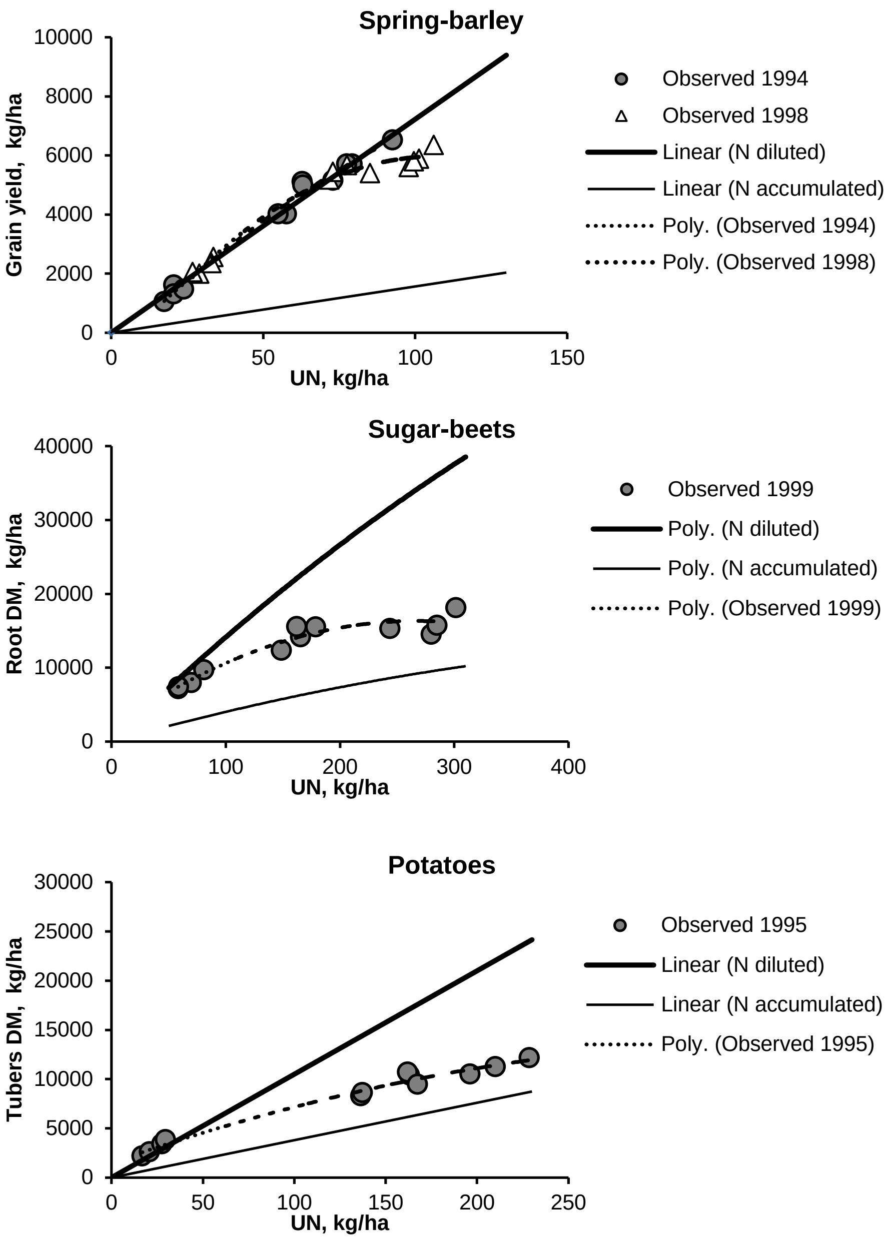


**Fig. 4.1.** Relationship between yield and uptake of N for spring-barley, sugar-beets and potatoes. The lines diluted and accumulated stand for $Y_N^d$ and $Y_N^a$, respectively. The values of their slopes are 72.3 and 15.7 for spring-barley, 135 and 38 for sugar-beets, 105 and 38 for potatoes. Parameters of regression equations and related properties are shown in Table 4.3. Uptake of potato refers to tuber plus foliage. N amounts in potato foliage were set at 0.188 times the quantities of N in potato tuber (Velthof & Van Erp, 1999).

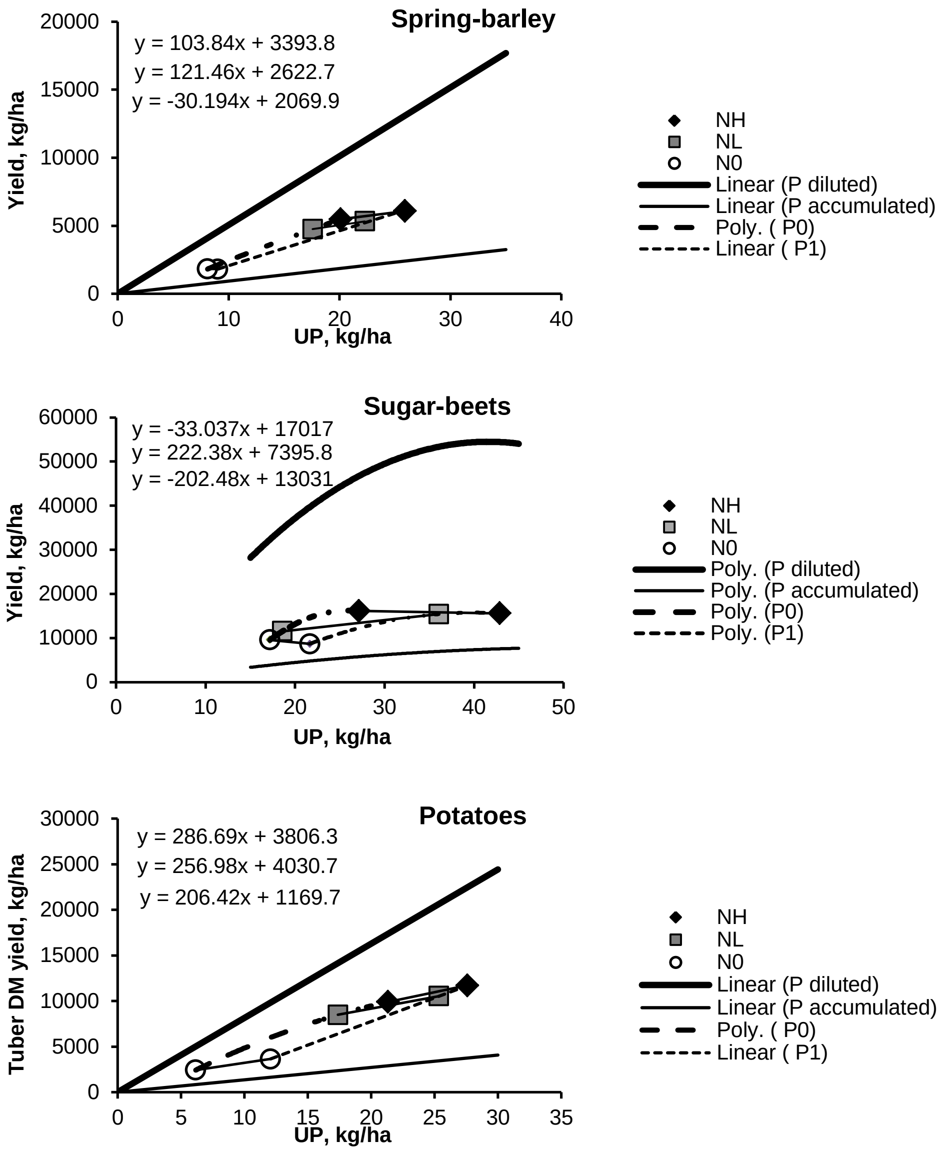


**Fig. 4.2.** Relationships between yields and uptake of P for spring-barley, sugar-beets and potatoes. Spring-barley data of 1994 and 1998 were averaged. The amounts of P in potato foliage were set at 0.164 times the quantities of P in potato tubers (Velthof & Van Erp, 1999). The lines diluted and accumulated stand for $Y_P^d$ and $Y_P^a$, respectively. The values of their slopes are shown as $PhEP_{max}$ and $PhEP_{min}$ in Table 4.2. The dotted lines represent the parabolic relations between Y and UP, at P0 and P1, of which the parameter values are given in Table 4.4. Each point at the levels NH, NL and N0 represents the average of four yield-UP combinations (two replicates, K0 and K1), either at P0 or at P1. The linear regression equations in the graphs refer to the lines connecting these points at the levels NH, NL and N0.

At higher UN levels, N became a little accumulated in sugar-beets and potatoes, but not in spring-barley. The curves of spring-barley were even somewhat above $Y_N^d$ between UNs of about 27 and 74 kg $ha^{-1}$, indicating very efficient use of absorbed N. The values of $UN_m$ for maximum yield of spring-barley 1994 and potatoes in Table 4.3 exceeded those of $UN_{max}$ as calculated in Chapter 3 (Table 3.4), implying that the observed UNs were not large enough to reach the highest possible yield in relation to uptake and supply of N.

### *4.3.3. PhEP: yields (Y) in relation to uptake of phosphorus (UP)*

Figure 4.2 shows the relationships between yield and UP inclusive the extremes of $Y_P^d$ and $Y_P^a$. The values of the related $PhEP_{max}$ and $PhEP_{min}$ are shown in Table 4.2. For sugar-beets the relations between $Y_P^d$ and UP, and between $Y_P^a$ and UP were not linear (comparable to the situation with N in Figure 4.1), because the harvest index decreased with increasing UP. The equations were

$Y_P^d = -37.186 \cdot UP^2 + 3093.4 \cdot UP - 9843$ and
$Y_P^a = - 3.067 \cdot UP^2 + 328.32 \cdot UP – 886.86.$

For the range of observed UPs, these relations approximately came down to a $PhEP_{max}$ of 1650 and a $PhEP_{min}$ of 215 (Table 4.2). On average, the ratio of $PhEP_{max}/PhEP_{min}$ was about 5.4 for spring-barley, 7.7 for sugar-beets and 6.0 for potatoes. The relationships between spring-barley yield and UP did not differ between 1994 and 1998, and therefore the data of the two years were combined in Figure 4.2 and Table 4.4. The P0 and P1 lines in Figure 4.2 were calculated as the

**Table 4.4.**
Rounded values of the parameters of the polynomial regression lines P0 and P1 relating yield to UP in Figure 4.2, calculated $UP_m$ for maximum or minimum yield ($Y_m$). The parameters a, b and c refer to equations $y= ax^2 + bx + c$, where y is yield and x is UP, both in kg $ha^{-1}$.

| Crop | Curve | -a | b | c | $R^2$ | $UP_m$ | $Y_m$ |
|---|---|---|---|---|---|---|---|
| Spring-barley | P0 | 2.32 | 369 | -1003 | 0.9863 | 80[bc] | 13705[bc] |
| | P1 | 3.20 | 366 | -1335 | 0.9955 | 57[bc] | 9233[bc] |
| Sugar-beets | P0 | 87.4 | 4526 | -42288 | 0.6233 | 26 | 16282 |
| | P1 | 20.6 | 1649 | -17315 | 0.9940 | 40 | 15757 |
| Potatoes [a] | P0 | 11.0 | 797 | -2040 | 0.9931 | 36 | 12439 |
| | P1 | -0.1588 | 513 | -2545 | 0.9915 | -1614[d] | -416062[d] |

[a] The quantity of P in foliage was set at 0.164 times the quantity of P in potato tuber (Velthof & Van Erp, 1999)
[b] Not realistic as yield was almost linearly related to UP.
[c] $UP_m$ and $Y_m$ (far) beyond measured UP
[d] $UP_m$ refers to UN at minimum value of y since the quadratic term (a) of the polynomial regression equation has a positive sign; non-realistic values of $UP_m$ and $Y_m$.

polynomial equations relating yield to UP at P0 and P1. Their parameter values are given in Table 4.4.

They have a position in between the extremes of $Y_P^d$ and $Y_P^a$ in Figure 4.2. The P0 lines are situated above the P1 lines, illustrating that physiological P use efficiency (PhEP) was greater at P0 than at P1. The spring-barley values of $UP_m$ and $Y_m$ in Table 4.4 were beyond the observed range of UPs indicating that yields could be much higher if UPs were higher. As described in Chapter 3, UP was limited by UN (Figure 3.3), which in turn was limited by N input (Figure 3.1). The P0 line of sugar-beets has a much lower $R^2$-value than the other regression lines (Table 4.4). This is a consequence of the low value of UP at NLP0 as shown in Chapter 3 (Section 3.3.4; Table 3.6). Also in Figure 4.2, NL has a low position on the P0 line.

Most lines in Figure 4.2 are in the lower half of the envelope between $Y_P^d$ and $Y_P^a$, revealing once again that P was sufficiently available; only the P0 line of potatoes is (just) in the upper half.
The regression coefficients of the linear equations in Figure 4.2 represent the relationship between $\Delta$YP and $\Delta$UP. Their slopes increase going from N0 to NL to NH for potatoes, indicating almost classical positive NP interactions for this crop. For spring-barley and sugar-beets the change in slopes is less regular.

*4.3.4. PhEK: yields (Y) in relation to uptake of potassium (UK)*
Figure 4.3 shows the relationships between yield and UK. The slopes of extreme lines of $Y_K^d$ and $Y_K^a$ have on average a ratio ($PhEK_{max}/PhEK_{min}$) of about 3.8 for spring-barley, 7.2 for sugar-beets, and 4.4 for potatoes. The experimentally established relations between yield and K uptake of potatoes (Velthof & Van Erp, 1999) were YKD = 0.23 (UK – 9.9) and YKA = 0.15 (UK – 9.9), where YKD and YKA have the same meaning as $Y_K^d$ and $Y_K^a$. The corresponding values of $PhEK_{max}$ and $PhEK_{min}$ were found to be 54.7 and 35.7, and *m* ($PhEK_{med}$, Equation 4.8) was 45.2 kg $kg^{-1}$. Following the same procedure as above for N and P, and taking into account that $MFK_{max}/MFK_{min}$ was 4.18 (Table 4.1), $PhEK_{max}$ and $PhEK_{min}$ were calculated to be 74 and 17 kg $kg^{-1}$, respectively (Figure 4.3, Table 4.2).

The K0 lines almost coincide with the K1 lines in Figure 4.3, revealing little difference in physiological K use efficiency (PhEK) between K0 and K1. Only for potatoes, the K0 line is clearly above the K1 line. The points N0, NL and NH on the dotted lines in Figure 4.3 were averaged across P0 and P1. The points and lines were situated in the lower half between the extremes of $Y_K^d$ and $Y_K^a$ for sugar-beets and spring-barley 1994, in the middle for spring-barley 1998, and in the upper half for potatoes. The lines for relationships between spring-barley yield and

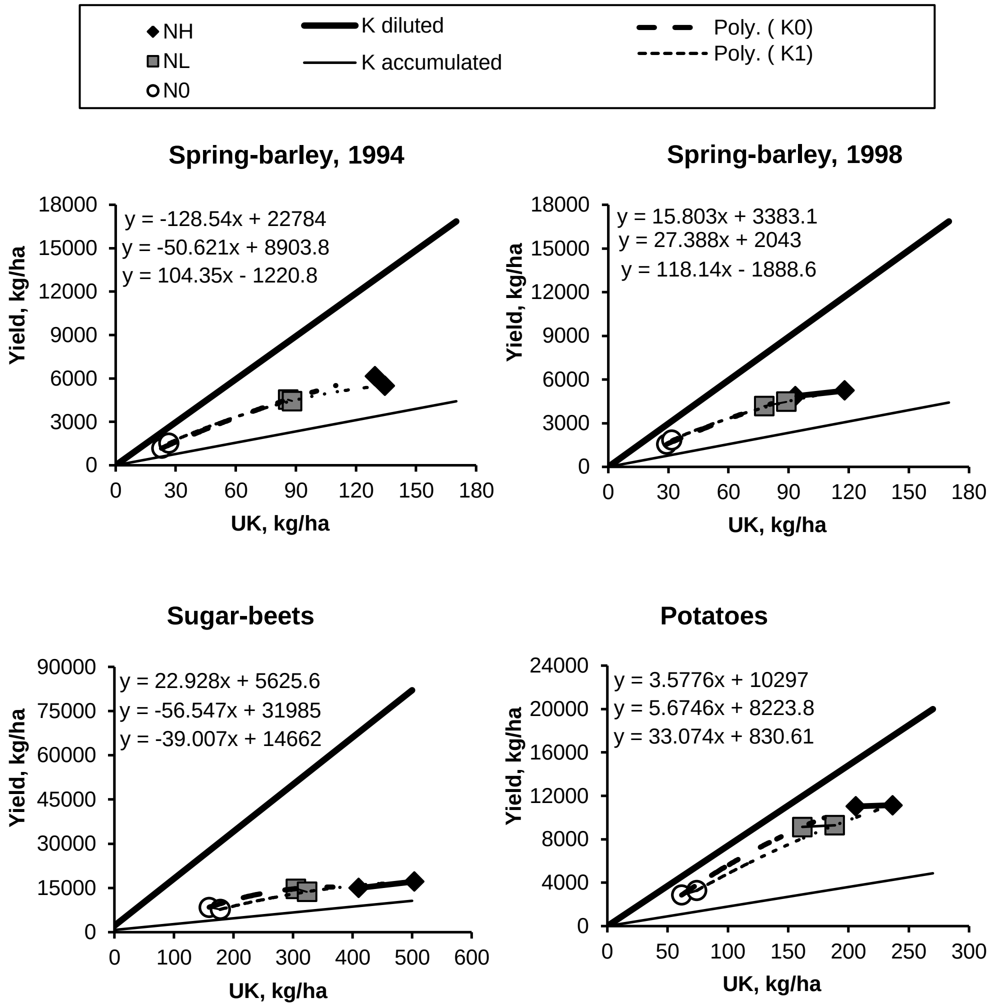


**Fig. 4.3**. Relationship between yields and uptake of K for spring-barley 1994 and 1998, sugar-beets and potatoes. The amounts of K in potato foliage were set at 0.195 times the quantities of K in potato tuber (Velthof & Van Erp, 1999). The lines diluted and accumulated stand for $Y_K^d$ and $Y_K^a$, respectively. The values of their slopes are shown $PhEK_{max}$ and $PhEK_{min}$ in Table 4.2. The dotted lines represent the parabolic relations between Y and UK at K0 and K1 of which the parameter values are given in Table 4.5. Each point at the levels N0, NL and NH represents the average of four UK–yield combinations (two replicates, P0 and P1), either at K0 or at K1. The linear regression equations in the graph refer to the lines connecting these points.

UK were at somewhat higher positions in the graphs of 1998 than those of 1994, indicating higher PhEK or smaller K abundance in 1998. Therefore, the data of the two years were not combined in Figure 4.3 and Table 4.5. Potato was the only crop with consistently positive values of fertilizer $\Delta Y/\Delta UK$ (regression equations in

Figure 4.3). In 5 of the 9 cases of the other crops, regression coefficients of the linear equations in Figure 4.3 were negative. In view of the small differences between K0 and K1, and the variation in the data, the effect of fertilizer K on yield of these crops must be considered negligible; only for potatoes it was weakly positive (Figure 4.3).

*4.3.5 Relative physiological nutrient use efficiencies (RPhE)*

Table 4.6 summarizes the effects of N, P and K application on the relative physiological use efficiency (RPhE) of these nutrients. On average RPhEN was hardly affected by P application. At N0, RPhEN was close to 100% in all crops pointing to (almost) maximum dilution of N. In the case of potatoes, RPhEN was even above 100, maybe because of the rather rude method of estimating potato yields at maximum dilution and accumulation (Equations 4.8, Section 4.2.2). With increasing N application, RPhEN of sugar-beets and potatoes went to values below 50%, indicating that at those N levels shortage of N was not very severe anymore. RPhEN of spring-barley in 1994 remained high at NL and NH, as the curves in Figure 4.1 showed.

At P1, RPhEP was lower than at P0 demonstrating that application of P resulted in decreasing physiological use efficiency by the crops. RPhEP increased with increasing N application, especially at P0. Only in the case of potatoes, RPhEP at P0 was around 50% at NL and NH suggesting that P application could be beneficial at these N application levels. The decrease in RPhEP between P0 and P1 was relatively small for potatoes, another indication that the P supply to this crop was relatively modest. For the other crops RPhEP was always lower than or equal to 45% revealing absence of P deficiency.

At K1, RPhEK was lower than at K0, confirming the message of Figure 4.3 that input K was not efficiently spent by the crops. Only for spring-barley at N0 and NL, and for potatoes at NL and NH, RPhEK was above 50% suggesting some shortage of K. For spring-barley 1994 and sugar-beets RPhEK was really low at K0, confirming these crops could easily take up sufficient K from the soil alone. In 1998 RPhEK was higher than in 1994 suggesting that K supply to spring-barley decreased between these two years, as concluded also in Chapter 3 (Sections 3.4.4 and 3.4.6).

Although the trends in relative physiological efficiency (RPhE) showed substantial resemblance with those in uptake efficiency (UE), presented in the appendix of Chapter 3 (Table A.3.1), it was not justified to construct a summary graph of RPhE as was done for UE (Figure 3.5), because there were considerable differences among the crops in RPhE but not in UE.

**Table 4.5**.
Rounded values of the parameters of the K0 and K1 polynomial regression lines in Figure 4.3, and of $R^2$, calculated $UK_m$ for maximum yield ($Y_m$). The parameters *a, b* and *c* refer to equations y= $ax^2 + bx + c$, where y is yield and x is UK, both in kg $ha^{-1}$.

| Crop | Curve | -*a* | *b* | *c* | $R^2$ | $UK_m$ | $Y_m$ |
|---|---|---|---|---|---|---|---|
| Spring-barley 94 | K0 | 0.15 | 70 | -342 | 0.9889 | 235[b] | 7830[b] |
| | K1 | 0.22 | 73 | -225 | 0.9810 | 163 | 5706 |
| Spring-barley 98 | K0 | 0.70 | 141 | -1326 | 0.9980 | 100 | 5758 |
| | K1 | 0.32 | 92 | -303 | 0.9935 | 145 | 6402 |
| Sugar-beets | K0 | 0.15 | 110 | -5336 | 0.9913 | 378 | 15557 |
| | K1 | 0.04 | 58 | -877 | 0.9472 | 681[b] | 18935[b] |
| Potatoes [a] | K0 | 0.14 | 94 | -2374 | 0.9798 | 334[b] | 13331[b] |
| | K1 | 0.08 | 73 | -1706 | 0.9863 | 463[b] | 15260[b] |

[a] The quantity of K in foliage is set at 0.195 times the quantity of K in potato tuber (Velthof & Van Erp, 1999)
[b] $UK_m$ (far) beyond measured UK

**Table 4.6.**
Relative dilution or relative physiological efficiency (RPhE, %) of N, P and K in relation to fertilizer treatments, as calculated with Equation 4.12a.

| Crop | N level | RPhEN | | RPhEP | | RPhEK | |
|---|---|---|---|---|---|---|---|
| | | P0 | P1 | P0 | P1 | K0 | K1 |
| Spring-barley | N0 | 96 | 84 | 28 | 20 | 35 | 44 |
| 1994 | NL | 99 | 115 | 41 | 34 | 37 | 34 |
| | NH | 99 | 100 | 46 | 35 | 29 | 20 |
| Spring-barley | N0 | 101 | 104 | 33 | 31 | 67 | 64 |
| 1998 | NL | 93 | 103 | 42 | 36 | 60 | 48 |
| | NH | 75 | 77 | 44 | 34 | 48 | 30 |
| Sugar-beets | N0 | 83 | 88 | 16 | 13 | 21 | 16 |
| 1999 | NL | 48 | 55 | 41 | 15 | 18 | 13 |
| | NH | 19 | 22 | 27 | 10 | 10 | 9 |
| Potatoes [a] | N0 | 135 | 133 | 38 | 24 | 50 | 47 |
| 1995 | NL | 36 | 40 | 52 | 41 | 71 | 60 |
| | NH | 26 | 23 | 49 | 43 | 63 | 50 |
| **Average** | | **76** | **79** | **38** | **28** | **42** | **36** |

### *4.3.6. N, P and K balances in crops and in soil and input*

Crops took up a greater portion of limiting nutrients than of non-limiting nutrients (Appendix 3, Table A.3.1). Consequently, N, P and K were better balanced in the crops than in the available supplies, and the standard deviations of the fractions FN, FP and FK were smaller for the nutrients taken up (SD FΣU) than for the available supplies (SD FΣA), as shown in Appendix 4, Tables A.4.2 and A.4.3, and in Figure 4.4. When SD FΣA was less than 10 to 12%, however, SD FΣU equalled SD FΣA (Figure 4.4, left-hand graph). Relative physiological efficiency (RPhEΣU) was not clearly related to SD, neither to SD FΣU nor to SD FΣA (Figure 4.4, right-hand graph; Figure 4.5, middle graph).

Appendix 4, Table A.4.3 gives, per fertilizer treatment, the supplies of available N, P and K from soil and input, expressed in kCNE (using the conversion factors CFP and CFK as is explained in Appendix 4, Equations A.4.1a, A.4.1b), adds them up to ΣA, and presents fractions FN, FP and FK of ΣA.

The available nutrients at treatment N0P0K0 are shown as soil available nutrient (SA) in Table 4.7. SAN was only between 7 and 13 % of ΣSA. SAP varied between 38 and 47%, and SAK between 42 and 56%. Although these fractions showed considerable variations, it is obvious that the fractions of available N in the soil were much smaller than the fractions of P and K. In view of the underestimates of SAP, and especially of SAK (Chapter 3, Section 3.3.8), the actual fractions of SAN, SAP and SAK likely were smaller, somewhat larger, and noticeably larger, respectively, than the values mentioned in Table 4.7. Sugar-beets took up far more nutrients from the soil (ΣSA) than spring-barley, which at least partly may be ascribed to the longer growing season of sugar-beets. Potatoes had the lowest SAP and SAK values and the lowest ΣSA, thus confirming the reputation of potato roots to be weak in exploiting the soil for nutrients.

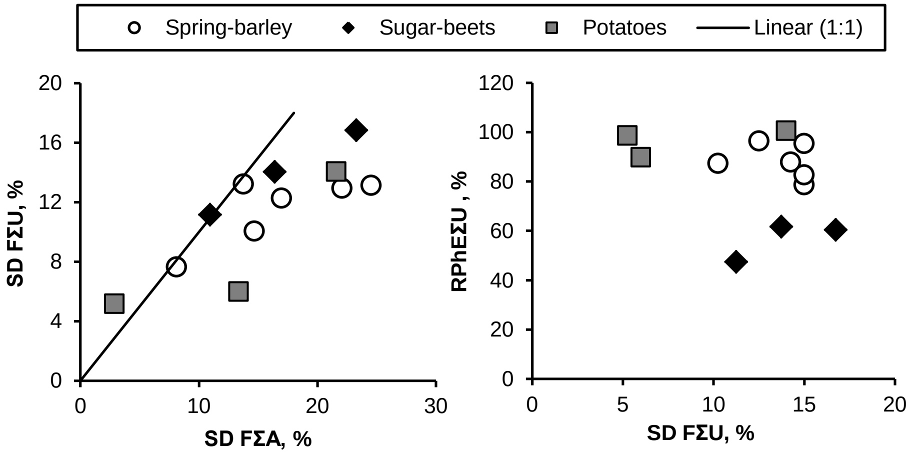


**Fig. 4.4.** Left-hand graph: standard deviation of the fractions FN, FP and FK of uptake (SD FΣU) versus standard deviation of the fractions FN, FP and FK of available N, P and K (SD FΣA) from soil and input. Each point is an average of the four PK treatments at one level of N input (N0, NL, NH). Right-hand graph: relative physiological efficiency of the sum of N, P and K taken up (RPhEΣU) in relation to the standard deviation (SD FΣU) of the fractions FN, FP and FK of the sum of N, P and K taken up.

**Table 4.7**.
Soil available (SA) N, P and K and their sum (ΣSA), expressed in kCNE $ha^{-1}$, and in fractions (FΣSA) of their sum with standard deviation of the fractions (SD); relative agronomic use efficiency of the sum of soil available N, P and K (RAEΣSA), as calculated with Equation 4.12c. See Appendix 4, Table A.4.3.

| | SA, kCNE $ha^{-1}$ | | | | FΣSA, % | | | | RAEΣSA, % |
|---|---|---|---|---|---|---|---|---|---|
| **Crop** | N | P | K | ΣSA | FN | FP | FK | SD | |
| S-barley 94 | 24 | 135 | 202 | 361 | 7 | 38 | 56 | 25 | 20 |
| S-barley 98 | 44 | 147 | 138 | 329 | 13 | 45 | 42 | 17 | 41 |
| Sugar-beets | 80 | 323 | 500 | 904 | 9 | 36 | 55 | 23 | 28 |
| Potatoes | 31 | 153 | 141 | 324 | 10 | 47 | 43 | 21 | 28 |
| *Average* | 45 | 189 | 245 | 479 | 10 | 41 | 49 | 22 | 29 |

The relative agronomic use efficiency of the sum of available soil and input nutrients is denoted by RAEΣA in Appendix 4, Table A.4.3. Its value was calculated with Equation 4.12c, and it is considered as a crop independent index of the agronomic efficiency at which the joint available N, P and K supplies from soil and input are used. RAEΣA at N0 was smaller in 1994 than in the other years. This is in line with the lowest FN and the largest SD FΣA at N0 in 1994 (Appendix 4, Table A.4.3), and with the qualification of this year as a 'bad' year among the (spring-barley) years of the long-term experiment (Chapter 2, Section 2.3.3.).

Appendix 4, Table A.4.3 also presents, for each experimental treatment, the standard deviations (SD FΣA) of the fractions of available N, P and K. The most balanced situations (smallest SD FΣA) were found at NL for potatoes and at NH for the other crops. The unfavourable effect of a large SD FΣA is illustrated in the graphs of Figure 4.5, where relative uptake, physiological and agronomic use efficiencies, averaged per N level (N0, NL, NH) were plotted versus the standard deviation of the fractions FN, FP and FK of ΣA (SD FΣA).

The points of spring-barley and potatoes in the graphs of relative uptake efficiency and relative agronomic use efficiency (Figure 4.5) followed a same pattern. Maximum values of relative efficiency were found where SD FΣA was less than 10 to 12%. In the case of sugar-beets, however, RPhEΣU and RAEΣA did not surpass 63 and 46%, respectively. This agrees with the low positions of the curves of sugar-beet yields versus UP and UK in Figures 4.2 and 4.3, respectively, and hence with the low RPhEP and RPhEK in Table 4.6. It supports the view that other factors than N, P and K supplies were limiting sugar-beet yields in this year (Table 2.4) and the values of RPhEΣU and RAEΣA.

*4.3.7. Balanced supplies of available NPK for water-limited yields*

The relationships established in Chapters 3 and 4 made it possible to calculate the required inputs for balanced NPK supplies at any target yield. Although the computations in Table 4.8 are straightforward, they look complicated because of the many distinctions that were made, such as between available supply and actual uptake, between available input and total input of N, P and K, and between balanced supplies ($\Sigma A_{bal}$) and supplies from the soil alone (SA). Another reason for the complicated appearance of Table 4.8 is that the relationships and values used stem not only from this chapter, but also from Chapters 2 and 3.

Water-limited yields were chosen as target yields in practical agriculture (Table 4.8, Line 1). Rounded estimates of water-limited yields were 8.5, 15, and 15 Mg $ha^{-1}$ for spring-barley, sugar-beets and potatoes, respectively (Reidsma et al., 2015). The corresponding required balanced supplies of available N, P and K (Lines 5, 6, and 7 in Table 4.8) were calculated with Equations 4.13d, e and f, respectively. In Lines 2, 3 and 4, RAEΣA was set at 0.9, based on the evidence from Figure 4.5 that at perfect balanced nutrient supplies*, i.e.* when SD FΣA stdev is 0, RAEΣA would be about 90% of the theoretically maximum agronomic use efficiency of available N, P and K together ($AE\Sigma A_{max}$). $PhE_{med}$ was calculated as the average of $PhE_{max}$ and $PhE_{min}$ (Equation 4.7).

Next, the corresponding uptakes of N ($\Sigma UN_{bal}$) were calculated (Line 9) using the ratio of N uptake to available N supply at balanced NPK supplies (Line 8), as derived from Appendix 3, Table A.3.1. The values of UN calculated in Line 9 were substituted in the regression equations of P0 in Figure 3.3 and of K0 in Figure 3.4 to find the uptake of P and K from the soil alone (SUP and SUK) at such UN values (Lines 10 and 11). The spring-barley outcomes of SUP and SUK for the years 1994 and 1998 were averaged. For SAN, the values of Table 3.11 could not directly be copied, because SAN was strongly related to rainfall in preceding winters (Chapter 2). Instead, use was made of the fact that N was maximum diluted in all crops when no fertilizer N was applied (Table 4.6; Figure 4.1).

This allowed the calculation of SUN by (N0 yield)/$PhEN_{max}$). Given the extreme N dilution in the crop, it was assumed that all available N was taken up, and hence SUN was equal to SAN. Using $PhEN_{max}$ of 72, 135 and 105 kg $kg^{-1}$ (Table 4.2) for spring-barley, sugar-beets and potatoes, respectively, the values of (N0 yield/$PhEN_{max}$) were calculated for all years between 1975 and 2002 in which those crops were grown, and the outcomes were adjusted to the average winter-rainfall of 305 mm in the way explained in Chapter 2, Section 2.2.5.

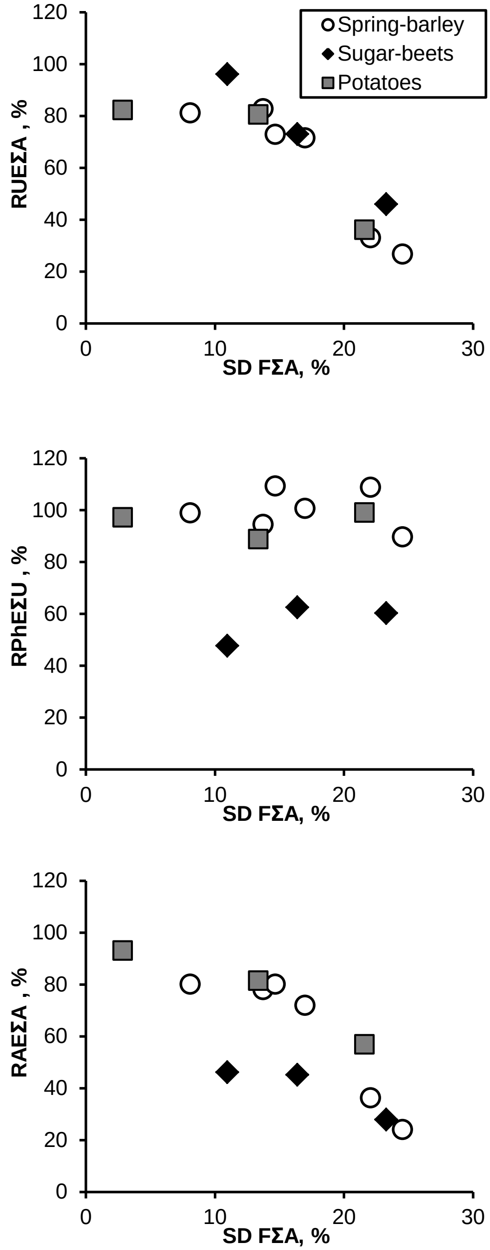


**Fig. 4.5**. Relative uptake efficiency (RUEΣA), relative physiological efficiency (RPhEΣU) and relative agronomic nutrient use efficiency (RAEΣA) as percentage of the theoretically maximum efficiencies in relation to the standard deviation (SD FΣA) of the fractions FN, FP and FK of available N, P and K from soil and input (ΣA). Each point is an average of the four PK treatments at one level of N input (N0, NL, NH).

The average SUN during this long-term experiment proved to be 38, 71 and 75 kg $ha^{-1}$ for spring-barley, sugar-beets and potatoes, respectively, and these outcomes were used as estimates of SAN in Table 4.8, Line 14.

Neither for SAP nor for SAK the numbers in Table 3.11 could be used, because the uptakes of P and K were related to UN (Figures 3.3 and 3.4). Therefore, first the UN values of Line 7 were substituted in the equations calculating UP at P0 (Figure 3.3) to find the P uptake from the soil alone at balanced NPK ($SUP_{bal}$; Line 10). The equations for K0 (Figure 3.4) were used for the calculation of $SUK_{bal}$ (Line 11). Next, $SUP_{bal}$ and $SUK_{bal}$ were divided by the U/A ratios at balanced nutrition presented in Lines 12 and 13, to arrive at $SAP_{bal}$, and $SAK_{bal}$ in Lines 15 and 16. The required inputs of *available* nutrients (IA) were calculated (Lines 17, 18, 19) as the difference between the total available supply needed ($\Sigma A_{bal}$) and the available supply from the soil alone (SA). As only a part ($AF_I$) of input nutrients is available, the total requirement of input nutrients (I) is larger than IA. It was calculated as $IA/AF_I$ (Lines 23, 24 and 25).

Table 4.8 shows that an input of 208 kg N would be required to reach water-limited yields of **spring-barley**, which is much more than was applied (Table 3.1). It is even more than $IN_{opt}$ (Table 3.4), the N input (IN) needed to get maximum uptakes of N. These are indications that more productive spring-barley varieties than were used in this long-term experiment would be necessary to attain the theoretical (simulated) water-limited yield of 8500 kg $ha^{-1}$.

For the target yield of **sugar-beets** root DM, an IN of 123 kg would be required, which is somewhat below the recommended 150 kg, the average of NL and NH (Table 3.1). From Chapter 3 it can be derived that at an IN of 123, UN would be 188 kg $ha^{-1}$ (Figure 3.1, Table 3.4), and the corresponding yield is calculated to be 14968 (with the regression equations using parameter values of Table 4.3), so indeed close to 15000 kg $ha^{-1}$, the target yield. For a target yield of 18000 kg, an IN of 162 kg would be required but still no P and K. The reason is that with an increased uptake of N, both SUP and SUK increase (lines 10 and 11), and IAP and IAK hardly change.

The picture for **potatoes** is different. The required IN of 184 kg $ha^{-1}$ (Table 4.8, Line 23) would result in an UN of 161 kg $ha^{-1}$ (Table 3.4) which is below $UN_m$ for maximum yield (Table 4.3). The yield corresponding to an UN of 161 kg $ha^{-1}$ is calculated to be 9768 (using parameters values of Table 4.3) so about 5000 kg below the target of 15000 kg. From application of the equation for the P1 curve (Table 4.4), it follows that an UP of 33.3 kg $ha^{-1}$ is required to reach 15000 kg $ha^{-1}$.

**Table 4.8.**
Calculation of required inputs to attain balanced supplies of available NPK for target (= water-limited) yields. SAN is set at 38, 71 and 75 kg ha$^{-1}$ for spring-barley, sugar-beets and potato.

| Line | | | S-barley | S-beets | Potatoes |
|---|---|---|---|---|---|
| 1 | Target yield (TY) | kg ha $^{-1}$ | 8500 | 15000 | 15000 |
| 2 | RAEΣA · $PhEN_{med}$ [ab] | kg kg $^{-1}$ | 39.6 | 77.85 | 64.35 |
| 3 | RAEΣA · $PhEP_{med}$ [ab] | kg kg $^{-1}$ | 269.6 | 839.3 | 427.5 |
| 4 | RAEΣA · $PhEK_{med}$ [ab] | kg kg $^{-1}$ | 56.3 | 85.1 | 41 |
| 5 | $\Sigma AN_{bal}$, kg ha $^{-1}$ | Lines 1/2 | 215 | 193 | 233 |
| 6 | $\Sigma AP_{bal}$, kg ha $^{-1}$ | Lines 1/3 | 31.5 | 17.9 | 35.1 |
| 7 | $\Sigma AK_{bal}$, kg ha $^{-1}$ | Lines 1/4 | 151.1 | 176.4 | 366.3 |
| 8 | $\Sigma UN_{bal/}\Sigma AN_{bal}$ [c] | | 0.79 | 1.00 | 0.89 |
| 9 | $\Sigma UN_{bal}$, kg ha $^{-1}$ | Lines 5 · 8 | 169.6 | 192.7 | 207.5 |
| 10 | $SUP_{bal}$, kg ha $^{-1}$ | Figure 3.3, P0 | 28.9 | 21.4 | 24 |
| 11 | $SUK_{bal}$, kg ha $^{-1}$ | Figure 3.4, K0 | 211 | 326 | 206 |
| 12 | $\Sigma UP_{bal}/\Sigma AP_{bal}$ [c] | | 0.945 | 0.95 | 0.83 |
| 13 | $\Sigma UK_{bal}/\Sigma AK_{bal}$ [c] | | 0.935 | 0.95 | 0.74 |
| 14 | SAN, kg ha $^{-1}$ | See text | 38 | 71 | 75 |
| 15 | SAP, kg ha $^{-1}$ | Lines 10/12 | 30.5 | 22.5 | 28.9 |
| 16 | SAK, kg ha $^{-1}$ | Lines 11/13 | 225.9 | 343.2 | 278.4 |
| 17 | IAN, kg ha$^{-1}$ | Lines 5 – 14 | 177 | 122 | 158 |
| 18 | IAP, kg ha$^{-1}$ | Lines 6 – 15 | 1.0 | -4.6 | 6.2 |
| 19 | IAK, kg ha$^{-1}$ | Lines 7 – 16 | -75 | -167 | 88 |
| 20 | $AF_{IN}$, % | Table 3.11 | 85 | 99 | 86 |
| 21 | $AF_{IP}$, % | Table 3.11 | 25 | 24 | 6 |
| 22 | $AF_{IK}$, % | Table 3.11 | 40 | 100 | 100 |
| 23 | IN, kg ha $^{-1}$ | 100 · Lines 17/20 | 208 | 123 | 184 |
| 24 | IP, kg ha $^{-1}$ | 100 · Lines 18/21 | 4 | 0 | 103 |
| 25 | IK, kg ha $^{-1}$ | 100 · Lines 19/22 | 0 | 0 | 88 |

[a] $RAE\Sigma A_{bal}$ is set at 0.9. See Figure 4.5.
[b] $PhE_{med}$ is calculated as 0.5 · ($PhE_{max}$ + $PhE_{min}$); $PhE_{max}$ and $PhE_{min}$ are shown in Table 4.2.
[c] From Appendix 3, Table A.3.1.

Application of the equation for the K1 curve (Table 4.5) would result in a maximum yield of 15260 kg ha$^{-1}$, at an optimum UK of 463 kg ha$^{-1}$. The calculated optimum UK of 463 kg ha$^{-1}$, however, was found at K1. It does not refer to situations of balanced nutrition, but to a less balanced and less efficient composition of available N, P and K. Hence, the calculated UK of 463 in Table 4.5 is larger than the $UK_{bal}$ of 206 kg ha$^{-1}$ (Line 11 in Table 4.8). In Table 4.8, the required IP and IK for potatoes are 103 and 88 kg ha$^{-1}$, respectively, higher than the applied rate of 87 kg P and considerably higher than the applied rate of 41 kg K (Table 3.1). Thus, although the actual application rates of N (160 and 320) to potatoes were in the right range, yields remained below the target tuber DM yield of 15000 kg ha$^{-1}$ because the applications of P and especially of K in the long-term experiment were too low.

## 4.4. Discussion

*4.4.1. General*

The results of the present chapter confirmed the conclusions of Chapters 2 and 3 that nitrogen was the overriding growth-limiting factor on this former sea-bottom soil. The study showed that N was maximally diluted in the crops, especially in spring-barley in 1994 (Figure 4.1), while P and K were closer to accumulation than to dilution, except in the cases of potatoes (Figures 4.2 and 4.3) and of spring-barley 1998 for K (Figure 4.3). Only potato could consistently make use of applied P and K in terms of increased uptake as well as increased production, while spring-barley and sugar-beets mainly increased the accumulation of P and K (Figures 4.2 and 4.3). Such phenomena of luxury consumption are rather common, even for potatoes, as was already shown in the forties (Nelson & Hawkins, 1947).

Application of the concept of crop nutrient equivalents (CNE) made it possible to judge whether the uptakes and the joint supplies from soil and input of available N, P and K were balanced or not. The soil supplies of available N, P and K, expressed in kCNE, were far from balanced (Table 4.7) and very low in N. Even at the highest N rates (NH) that were applied in this long-term experiment, the fraction of N in the sum of available N, P and K remained below 30%, again with the exception of potatoes (Appendix 4, Table A.4.3). The application of N at NH was too high for potatoes, creating sufficiency of available N (FN of about 50%) and a reduction of the relative agronomic use efficiency RAEΣA of NPK roughly from an average of 81% at NL to 72% at NH (Appendix 4, Table A.4.3).

*4.4.2. Relationships between yield and nitrogen*

The curves of sugar-beets and potatoes in Figure 4.1 somewhat levelled off upon application of N indicating less dilution and even some accumulation of crop N. The line of spring-barley in 1994 remained steep, implying a more efficient physiological use of absorbed N in 1994 than in 1998, which may at least partly be a consequence of the higher UP and UK in 1994. The data of relative physiological efficiency (or relative dilution) of absorbed N (Table 4.6), were higher in 1994 than in 1998 pointing to a more severe N shortage in 1994. This was in line with the (not shown) lower N mass fractions in grains as well as in straw in 1994 than in 1998. Likewise, the greater average N harvest index (the ratio of N in grains to N in grains and straw) in 1994 than in 1998, being 0.92 and 0.78, respectively, reflecting a stronger N transfer from straw to grain in 1994, pointed towards a graver N limitation in 1994.

Tables 4.3 and 3.5 showed that **spring-barley** yield in 1994 theoretically could have been above the water-limited yield of 8500 kg at an optimum UN of about 200 kg $ha^{-1}$. The actual maximum UN by spring-barley in 1994, however, was about 80 kg (Table 3.3), and the corresponding yield was about 6000 kg $ha^{-1}$, which is 2500 kg below the target yield. In 1998, the optimum UN was 107 kg $ha^{-1}$, with a corresponding maximum yield of 5968 kg $ha^{-1}$ (Table 4.3), and required N input of 105 kg $ha^{-1}$, being above IN at NH in 1998 (Table 3.1). Hence, neither in 1994 nor in 1998, it would have been possible to attain a water-limited yield of 8500 kg $ha^{-1}$.

Taking into account that for **sugar-beets** $AF_{IN}$ is 99% and $\Sigma UN_{bal/}\Sigma AN_{bal}$ is 1.00 (Table 4.8) and that $PhEN_{med}$ is between 80 and 93 kg $kg^{-1}$ depending on the harvest index (Table 4.2), the yield increase per kg applied N is expected to have varied between 79 and 92 in 1999. This outcome is somewhat lower than the 90 to 100 kg $kg^{-1}$ found at optimum N application rates and favourable weather conditions in Flevoland (De Koeyer et al., 2003). Because that study, referring to the years between 1975 and 1996, did not include the year 1999, its data cannot directly explain the (small) differences in agronomic N use efficiency by sugar-beets between for the two studies.

At high IN, UN of sugar-beets did not level off (Figure 3.1), but yields in relation to UN did (Figure 4.1). In the case of potatoes, UN levelled off above 160 kg $ha^{-1}$ IN, while tuber yields were practically linearly related to UN. The slowing down of N uptake by potatoes above 160 kg $ha^{-1}$ IN may have been related to relatively strong P dilution (or rather high relative physiological P use efficiency, RPhEP) at P0 (Table 4.6). The stabilization of sugar-beets yields at large UN likely must be ascribed to the fact that the measured yields of 12 – 18 Mg $ha^{-1}$ were comparable to water-limited sugar-beet yields (Reidsma et al., 2015, Wolf et al., 2012), while measured potato yields of 10 – 12 Mg $ha^{-1}$ still remained below the range of water-limited yields.

The ratios of tuber DM to UN for potatoes in Figure 4.1 were about 80 to 90% of those found on sandy soils in Wageningen (Vos, 1997), which may partly have been caused by differences in assumptions made about the ratio of ‘N in potato tubers to N in foliage’ which was 0.188 in this study versus 0.14 in the study by Vos.

### *4.4.3. Relationships between yield, phosphorus and potassium*

The relations between **spring-barley** yield and UP were practically the same in 1994 and 1998, suggesting that crop P provision did not change. Hence, the two years were taken together in Figure 4.2 and Table 4.4. The calculated optimum values of UP and the corresponding maximum yields were far beyond the real UP data (Table 4.4).

The relations between yield and UK (K0 curve in Figure 4.3), however, showed higher yields at similar UKs and hence higher RPhEK (Table 4.6) in 1998. It is an, albeit weak, indication that in 1998 soil K provision was relatively scarce compared to 1994, a signal that also showed up in the values of SAK in Table 4.7.

**Sugar-beets** did not suffer from P and K shortage (Figures 4.2 and 4.3). Compared to the other crops, sugar-beets experienced relatively less N deficiency than other crops; at N0, its RPhEN was relatively low (Table 4.6). Apparently, this crop was able to absorb nutrients from soil as well as from inputs in an efficient way (Table 3.11; Appendix 3, Table A.3.1).

**Potatoes** had higher RPhEP and RPhEK values (Table 4.6) and so stronger relative P and K dilution than the other crops, which supported the reputation of potatoes as weak nutrient absorbers. The complicated and therefore rather risky establishment of potato yields at maximum dilution and maximum accumulation (Equations 4.8a,b,c in Section 4.2.2), however, may have been too rude and have contributed to overestimating PhEs of potatoes.
Compared to the CFK values of 0.70, 0.90 and 1.55, for spring-barley, sugar-beets, and potatoes (Table 4.2), the observed UKs were very high, except for potatoes when N was applied (NL and NH).

*4.4.4. Required nutrients for water-limited yield*

**Sugar-beets** were the only crop that was able to attain the assumed maximum yield that was possible under the prevailing conditions of climate and the quantities of nutrients applied in this long-term experiment (Table 4.8). Actually, more nutrients were applied than the crop really needed. Input of P and K could have been left out for sugar-beets, even if the target yield would be 18000 kg $ha^{-1}$.

**Potatoes** received more than sufficient N but too little P and K to reach the maximum possible yield of 15000 kg $ha^{-1}$ of tuber dry matter. Whether such a yield could be attained with every potato variety is uncertain in view of the fact that only 3 or 4 varieties yielded that much, despite the wide variations in yield above and below the averages of 12 to 13000 kg $ha^{-1}$ of tuber dry matter found in the period 1960 -1995 (Rijk et al, 2013).

The factor preventing **spring-barley** to produce more than 6 to 7000 kg $ha^{-1}$ in this long-term trial was the actual application rate of N. It was not more than 107 kg $ha^{-1}$ resulting in a maximum N uptake of about 125 kg $ha^{-1}$, while according to Table 4.8 an application of 208 kg $ha^{-1}$ is required to get an N uptake of 170 kg $ha^{-1}$, needed for a potential yield of 8500 kg $ha^{-1}$. Spring-barley yields of 8500 kg $ha^{-1}$ were not observed before 2002, the last year of our long-term experiment, and only one or two times between 2003 and 2010 (Rijk et al, 2013). The $N_{max}$ limit for spring-barley in EU is 150 kg ha $^{-1}$ for expected standard yields of 5500 kg ha $^{-1}$, plus 20 kg ha $^{-1}$ per additional yield of 1000 kg (CBS, PBL, Wageningen UR, 2014). This would result in an application of 210 kg ha$^{-1}$ for the maximum possible yield of 8500 kg ha$^{-1}$, which is the same input of N as calculated in Table 4.8.

*4.4.5. Appraisal of the nutrient use efficiency*

In this study, three categories of nutrient use efficiency (E) were distinguished: uptake efficiency (UE = U/A), physiological efficiency (PhE = Y/U), and agronomic efficiency (AE = Y/A). The acronym Y stands for yield (of the economic crop parts), U for uptake (in the economic as well as in the other crop parts), and A for available amount of nutrients supplied by soil and input. So, the term efficiency may refer to the use efficiency of the stock of available nutrients (uptake efficiency), the production of harvestable products per unit of nutrients taken uptake (physiological efficiency), and the production of harvestable products per unit of available nutrients (agronomic efficiency).

The concept of ‘nutrient use efficiency’ got more relevance and applicability by the introduction of ‘relative’ criterions, *i.e.* comparative to a certain (theoretical) maximum: actual uptake compared to available quantity; physiological efficiency and agronomic efficiency as compared to maximum production per unit of absorbed nutrient and available nutrient, respectively, that is attained at maximum dilution of that nutrient in the crop. Using relative efficiencies, nutrient use efficiency by different crops could be compared.

The ‘relative agronomic use efficiency of all available nutrients’ (RAEΣA) may serve as an overall index of the environmental and economic soundness of agricultural practices.

The restriction to ‘available’ nutrients is not common in crop nutrition studies, neither is it usual to join the nutrient supplies by soil and input. Also, the concept of nutrient (or specifically nitrogen) use efficiency (NUE) found in literature does not exactly coincide with what is meant in this study. The EU Nitrogen Expert Panel (2015) concept for NUE is based on the mass balance of a system: NUE = N output/N input, where N output refers to N in harvested products removed from the system, and N input consists of N in fertilizer, biological N fixation and N deposition. The EU Nitrogen Expert Panel recommended NUE to be less than 90% in order to avoid nutrient mining and soil degradation, and more than 50% to avoid inefficient N use. The area in between the two lines are considered the desired range for NUE. Further, N surplus should not be more than 80 kg per ha.

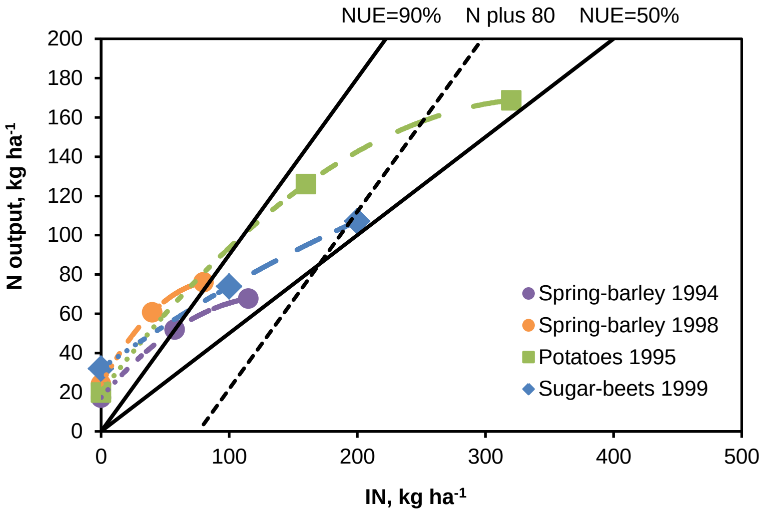


**Fig. 4.6**. N output by spring-barley, sugar-beets and potatoes versus N input, in the model of the NUE indicator proposed by the EU Nitrogen Expert Panel.

In Figure 4.6, N output is the N in the economically interesting crop components (grain, roots, tubers), only. The assumption is that N in 'stover' returns to the soil. When the input of N was 50 kg or more all outputs were in the desired range, at lower N input there was a risk of soil N mining. At NH (200 kg IN to sugar-beets; 320 kg IN to potatoes), the outputs were close to inefficient N use according to the EU panel criteria.

The output of P was about equal (spring-barley) to or somewhat smaller (sugar-beets, potato) than the input of P. The output of K is much greater than the input of K leading to soil K mining. When no P or K was applied, soil P and soil K were mined, but after 28 years, soil degradation was not (yet) noticed (see Section 5.4).

The conceptions about nutrient use efficiency depend on the objectives of study. While the EU Nitrogen Expert Panel was mainly concerned about environmental issues, in our study we tried to get insight in long-term changes in soil fertility and the differences among different crops in responses to nutrient inputs. The study on N and P capture efficiencies in sub-Saharan Africa (Chokowo et al., 2010) defined capture efficiency as (uptake/supply from soil and input) which resembles uptake efficiency in Chapter 3; the nutrient supply from the soil was assessed in a similar way and referred to 'available' nutrients, but in the African study the supply from input was not restricted to 'available' nutrients in but simply to the total quantity of input nutrients.

The method we used to assess ‘available’ nutrients is pragmatic rather than sophisticated, and avoids endless discussions on availability. The same approach was applied for soils as for inputs. This has the advantage that the joint supplies by soils and inputs refer to nutrients of equal availability, so to nutrients that are equivalent to the crop.

### *4.4.6. Surplus value of the concept of balanced supplies of available nitrogen, phosphorus and potassium*

Not many field studies were engaged in striving at a balance among available N, P and K supplies from soil and input. A major obstacle to such balance or equilibrium investigations is the lack of a suitable tool to determine whether N, P and K supplies are balanced or not. In this chapter, it was the system of expressing quantities of nutrients in ‘crop nutrient equivalents’ that made it possible to value quantities of different nutrients in a direct and simple way. Because one kCNE of N has the same relation to crop production as one kCNE of P or one kCNE of K, balance merely means that the numbers of N, P and K expressed in kCNE are equally large. This does not mean that they should be precisely equal. There is quite some leeway allowed; the standard deviation of the fractions of N, P and K in their combined supplies should not exceed 10%. It is comparable with the plateau level in classical yield curves of one nutrient. From Figure 4.5, it follows that the relative agronomic nutrient use efficiency of the sum of available N, P and K is less than 90% of its theoretical maximum, when the standard deviation of the fractions of N, P and K of the combined available supplies are more than 10 %.

The supplies of available N, P and K offer better possibilities to judge nutrient balance than the uptakes of N, P and K, because crops take up a relatively greater portion of limiting nutrients than of non-limiting nutrients, and therefore N, P and K are more in balance in crops than in soils and inputs. This weakens the value of foliar analysis as a diagnostic tool for plant nutrient status.
The concept of CNE for quantitative comparison of N, P and K is less complicated than the well-known diagnosis and recommendation integrated system (DRIS) introduced about half a century ago for perennial crops and later used for annual crops as well (Beaufils, 1971; Bailey et al., 1997).

## 4.5. Conclusions

The information on physiological and agronomic nutrient use efficiency collected in this long-term experiment revealed once more that the soil was low in N, high in P and still higher in K.

The concept of crop nutrient equivalents (CNE) allowed an examination of whether N, P and K in supplies and uptake were well equilibrated, by calculating the sum of N, P and K and the fractions of each nutrient in the sum of N, P and K. The standard deviations of the fractions of available N, P and K were larger than the standard deviations of the fractions of N, P and K taken up by the crop because the uptake efficiencies of the deficient nutrients were greater than the uptake efficiencies of the other nutrients.
Further, it proved essential in evaluating N, P and K balances to consider only the nutrients that were available and not the total amounts of the nutrients, and to combine the supplies in soils and inputs. The available quantity of a nutrient was estimated as the maximum uptake of that nutrient by the crop in situations where the nutrient was by far the most limiting growth factor.

The supplies of available N, P and K in this Flevoland soil were far out of balance, with less than 10% of N in the sum of N, P and K expressed in CNE. N was maximum diluted in the crops when no N was applied. P and K were in the middle between maximum accumulation and maximum dilution in spring-barley and potatoes, and closer to maximum accumulation than to maximum dilution in sugar-beets. The supplies of available N, P and K ($\Sigma AN_{kCNE}$, $\Sigma SAP_{kCNE}$, $\Sigma AK_{kCNE}$) in soil plus input together were most balanced at high rates of N and no applications of P and K in the case of sugar-beets and spring-barley, and at medium rates of N in combination with P and especially with K application in the case of potatoes. At these NPK inputs, the relative agronomic use efficiency of the sum of available N, P and K (RAEΣA) was greater than at other treatments and about 90% of the theoretical $AE\Sigma A_{max}$.

Potatoes were weaker in exploiting soil nutrients, and in absorbing fertilizer P than sugar-beets and spring-barley, and they required larger P and K inputs to attain water-limited yields than was recommended and practiced in the trial.
The standard N applications (Chapter 2, Section 2.2.2) of 150 kg N to sugar-beets and of 210 kg for potatoes were correct, but the application of about 55 kg N to spring-barley was far too low to reach water-limited production. Moreover, the used spring-barley varieties likely could not produce as much as the highest yielding ones at present.

Application of P and K to potatoes only in a rotation with cereals, sugar-beets and potatoes would suffice to continue cropping for another great, yet unknown number of years.

## Appendix 4.

QUEFTS principles applied for the calculation of the balance among N, P and K

*A.4.1. Relations between nutrient uptake and yield.*

The pivot of QUEFTS is formed by the relations between nutrient uptake and yield (Janssen et al. 1970). Such relations have been found to vary between two extremes. When the nutrient under consideration is very scarce compared to the other nutrients and other growth factors, it is maximum diluted in the crop, and its physiological use efficiency (PhE, the ratio of yield (Y) to uptake (U)) has its maximum value ($PhE_{max}$). When the nutrient under consideration is amply available compared to the other nutrients and other growth factors it accumulates in the crop up to a maximum, and then its physiological use efficiency has a minimum value ($PhE_{min}$). The values of $PhE_{max}$ and $PhE_{min}$ are different for N, P and K, and vary among crops. Figure A.4.1 shows an example for maize. The bisector in the middle between the lines of dilution and accumulation has medium PhE values ($PhE_{med}$). This line represents balanced nutrition, the situation at which N, P and K are taken up in optimum proportions, while at $PhE_{max}$ and $PhE_{min}$ the nutrient uptakes are extremely out of balance. It follows from Figure A.4.1 that at balanced nutrition of maize: Y = 50 · UN, Y = 400 · UP, and Y = 75 · UK kg, or $PhEN_{med}$ = 50, $PhEP_{med}$ = 400, and $PhEK_{med}$ = 75 kg $kg^{-1}$. The proportions of N : P : K in the crop are then 1/50 : 1/400 : 1/75 = 1 : 0.125 : 0.667, equal to 1 : CFP : CFK (see Section A.4.3).

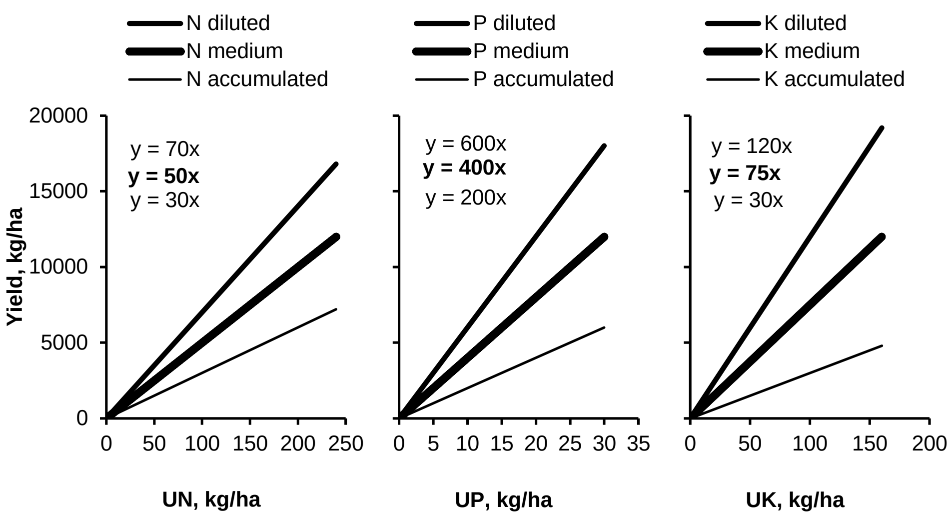


**Fig. A.4.1**. Relations between maize grain yield and uptake of N, P and K, as used in QUEFTS

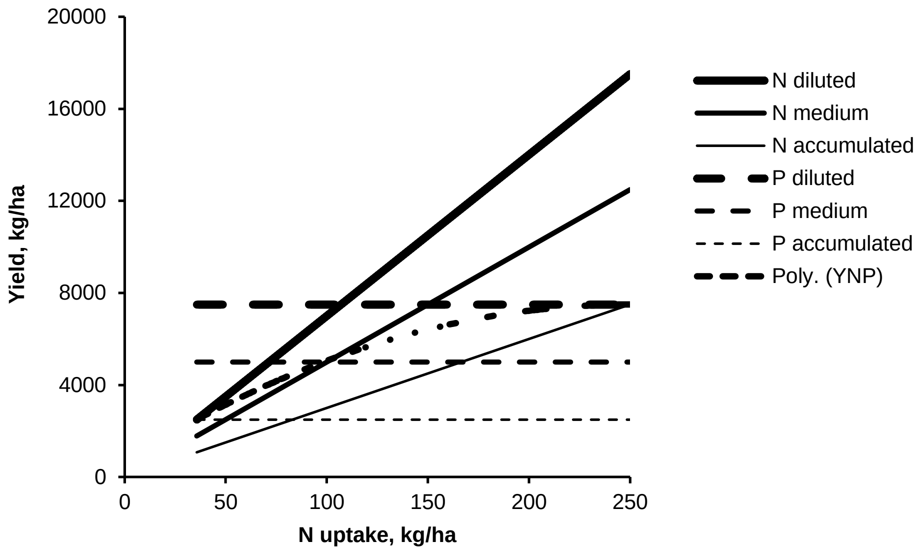


**Fig. A.4.2.** QUEFTS calculation of maize yield as a function of a varying uptake of N and a fixed uptake (12.5 kg $ha^{-1}$) of P.

*A.4.2. Calculation of yield in relation to the uptake of two nutrients.*

In Figure A.4.2, the lines of N diluted, N medium and N accumulated were calculated as Y= 70 · UN, 50 · UN and 30 · UN kg $ha^{-1}$, respectively. UP was fixed at 12.5 kg $ha^{-1}$, and the values of Y at P diluted, P medium and P accumulated were set at 600 · 12.5 = 7500, 400 · 12.5 = 5000, and 200 · 12.5 = 2500 kg $ha^{-1}$, respectively. The parabolic curve YNP is the calculated yield between the lowest and the highest possible yield. The lowest YNP (2500) is found at the point of intersection of 'N diluted' and 'P accumulated', and the highest YNP (7500) at the point of intersection of 'N accumulated' and 'P diluted'. At balanced uptakes of N (100 kg $ha^{-1}$) and P (12.5 kg $ha^{-1}$), QUEFTS calculated YNP to be 5050 kg $ha^{-1}$, close to the 5000 kg for the yield at the intersection of the lines of P medium and of N medium at an UN of 100 kg $ha^{-1}$. According to QUEFTS, the yield at balanced uptakes of two nutrients may be a little bit higher or lower than the yield at the intersection of the two medium lines, depending on the maximum and minimum PhE values of the two nutrients*, i.c.* on $PhEP_{max}$/ $PhEN_{min}$. If this ratio were 20.8, instead of 600/30 = 20 used in Figure A.4.2, the yield at the intersection of the two medium lines would be equal to YNP. See Table A.4.1.

Figure A.4.2 is a somewhat modified version of Figure 4 in the original QUEFTS paper (Janssen et al., 1990). More background information is presented in that article.

*A.4.3. Crop nutrient equivalents (CNE) and conversion factors.*

To facilitate judicious quantitative assessment of the balance among N, P and K, it was proposed (Janssen 1998, 2011) to express the quantities of N, P and K in units of (kilo) crop nutrient equivalents (k)CNE). A (k)CNE of any nutrient was defined as the quantity of that nutrient that, under conditions of balanced nutrition, has the same effect on yield as 1 (k)g of nitrogen (Janssen, 1998). Consequently, in the example of Figure A.4.1, 1 kCNE of P is equal to 50/400 = 0.125 kg of P; 1 kCNE of K is equal to 50/75 = 0.677 kg of K while 1 kCNE of N is by definition equal to 1 kg of N. At balanced nutrition, $PhE_{med}$ has equal values for N, P and K if their uptakes are expressed in kCNE; it is 50 kg/kCNE in the example of maize. The above ratios 50/400 and 50/75 were called CFP and CFK, respectively, where CF stands for 'conversion factor'. It follows that CFP and CFK can be calculated by:

$$CFP = (Y/UN_{kg})_{med} / (Y/UP_{kg})_{med} = PhEN_{med}/PhEP_{med} \quad \text{(Eq. A.4.1a)}$$

$$CFK = (Y/UN_{kg})_{med} / (Y/UK_{kg})_{med} = PhEN_{med}/PhEK_{med} \quad \text{(Eq. A.4.1b)}$$

In these equations, Y, UN, UP and UK are in kg or kg $ha^{-1}$, and PhE is in kg $kg^{-1}$. Figure A.4.3 shows the relationships of yield to uptake for the situation yield is expressed in kg $ha^{-1}$, and uptake in kCNE $ha^{-1}$.

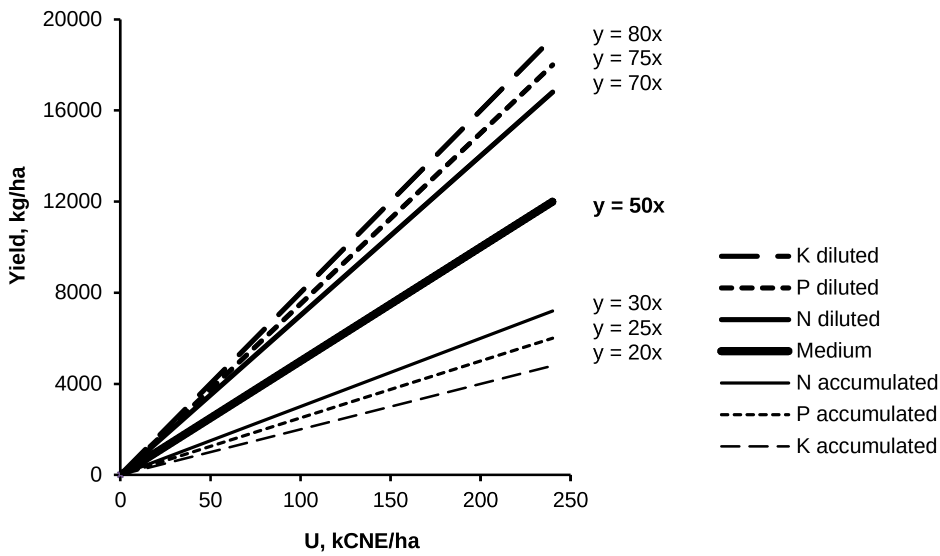


**Fig. A.4.3.** Relation between maize grain yield expressed in kg $ha^{-1}$ and uptake (U) of N, P or K, expressed in kCNE $ha^{-1}$.

*A.4.4. NPK combinations for maximum physiological nutrient use efficiency*

In Section 4.2.5 it was stated that the maximum value of the *physiological* efficiency of the sum of N, P and K taken up ($PhE\Sigma U_{kCNE,max}$) is found at or near to balanced uptakes of N, P and K. Balanced means that the uptakes of N, P and K, expressed in crop nutrient equivalents (CNE), are equal. By definition, PhEΣU is $Y_{NPK}/\Sigma U$, where ΣU is expressed in kCNE. Hence, at equal values of ΣU, $PhE\Sigma U_{kCNE}$ and $Y_{NPK}$ are maximum at the same kCNE values of UN, UP and UK. Figure 4.4 showed that at APM $PhE\Sigma U_{kCNE}$ was only weakly related to the balance of the uptakes of N, P and K.

The model QUEFTS assesses uptakes as functions of the supplies of N, P and K, and yields as functions of uptakes (Janssen et al., 1990). Applications of the QUEFTS model soon revealed the significance of balanced NPK supplies for maximum yields (Janssen et al., 1992).

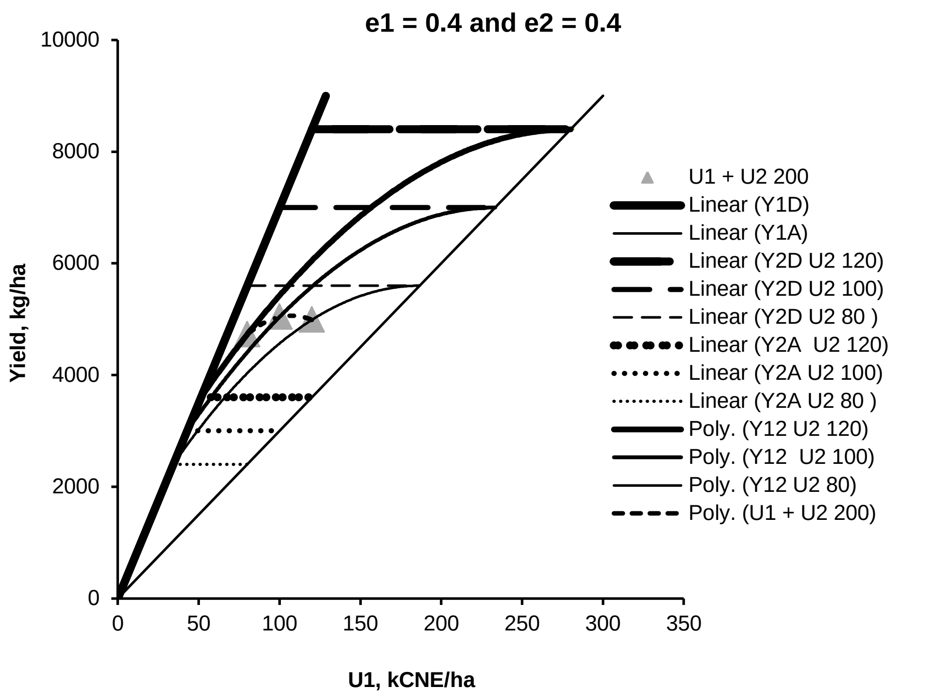


**Fig. A.4.4**. QUEFTS calculated yields as a function of varying uptakes of Nutrient 1 and fixed uptakes of Nutrient 2. The uptake of Nutrient 2 (U2) is, from top downwards, set at 120, 100 and 80 kCNE $ha^{-1}$. The points denoted by [U1 + U2 200] refer, from left to right to U1 of 80, 100 and 120 and to U2 of 120, 100 and 80 kCNE $ha^{-1}$. These yields are shown in Table A.4.1 as Y12 at $e_1$ and $e_2$ values of 0.4.

For demonstration purposes, the discussion here is limited to the uptake-yield relations of two nutrients, as shown in Figure A.4.2. The following QUEFTS equation was used for the calculation of YNP:

$$YNP = YPA + b_N \cdot (UN - UN_{min}) - c_N \cdot (UN - UN_{min})^2 \qquad \text{(Eq. A.4.2.a)}$$

If P uptake is plotted along the X-axis, the symbol for yield is YPN. It is calculated as:

$$YPN = YNA + b_P \cdot (UP - UP_{min}) - c_P \cdot (UP - UP_{min})^2 \qquad \text{(Eq. A.4.2.b)}$$

The coefficients b and c are found by:

$$b_N = 2 \cdot (YPD - YPA)/(UN_{max} - UN_{min}) \qquad \text{(Eq. A.4.3.a)}$$
$$b_P = 2 \cdot (YND - YNA)/(UP_{max} - UP_{min}) \qquad \text{(Eq. A.4.3.b)}$$

$$c_N = (YPD - YPA)/(UN_{max} - UN_{min})^2 \qquad \text{(Eq. A.4.3.c)}$$
$$c_P = (YND - YNA)/(UP_{max} - UP_{min})^2 \qquad \text{(Eq. A.4.3.d)}$$

When using these equations, it is convenient to express UN and UP in kCNE, and yields in kg. The terms and coefficients in Equations A.4.2 and A.4.3 are:

$YNA = UN \cdot PhEN_{min}$; $YND = UN \cdot PhEN_{max}$, and hence
$YND - YNA = UN \cdot (PhEN_{max} - PhEN_{min})$
$YPD = UP \cdot PhEP_{max}$; $YPA = UP \cdot PhEP_{min}$; and hence
$YPD - YPA = UP \cdot (PhEP_{max} - PhEP_{min})$;
PhE in kg $kCNE^{-1}$; Y in kg [ = kCNE · kg · $(kCNE)^{-1}$]

$UN_{max} = YPD/PhEN_{min} = UP \cdot PhEP_{max}/PhEN_{min}$
$UN_{min} = YPA/PhEN_{max} = UP \cdot PhEP_{min}/PhEN_{max}$
$UN_{max} - UN_{min} = UP \cdot [PhEP_{max}/PhEN_{min} - PhEP_{min}/PhEN_{max}]$

$UP_{max} = YND/PhEP_{min} = UN \cdot PhEN_{max}/PhEP_{min}$
$UP_{min} = YNA/PhEP_{max} = UN \cdot PhEN_{min}/PhEP_{max}$
$UP_{max} - UP_{min} = UN \cdot [PhEN_{max}/PhEP_{minx} - PhEN_{min}/PhEP_{max}]$; U in kCNE

At a given sum of UN plus UP, the ratio of UN to UP is optimum when the sum of YNP + YPN is maximum; more general: the ratio of U1 to U2 is optimum when the sum of Y12 + Y21 is maximum. It is shown below this is the case when U1 equals U2, provided $e_1$ has the same value as $e_2$. The meaning and value of $e_1$ follow from Equations 4.8a,b,c (Section 4.2.2), and are:

**Table A.4.1.** Values of QUEFTS calculated yields Y12, Y21 and (Y12 + Y21)/2 for various combinations of $e_1$ and $e_2$ and of U1 and U2.

| $e_1$ | $e_2$ | U1 | U2 | Y12 | Y21 | (Y12 + Y21)/2 | |
|---|---|---|---|---|---|---|---|
| | | | | | | kg | % of maximum |
| 0.6 | 0.6 | 80 | 120 | 3911 | 4267 | 4089 | 98.3 |
| | | 100 | 100 | 4160 | 4160 | *4160* | 100.0 |
| | | 120 | 80 | 4267 | 3911 | 4089 | 98.3 |
| 0.5 | 0.5 | 80 | 120 | 4406 | 4734 | 4570 | 97.5 |
| | | 100 | 100 | 4688 | 4688 | *4688* | *100.0* |
| | | 120 | 80 | 4734 | 4406 | 4570 | 97.5 |
| 0.4 | 0.4 | 80 | 120 | 4725 | 4988 | 4856 | 96.3 |
| | | 100 | 100 | 5040 | 5040 | *5040* | *100.0* |
| | | 120 | 80 | 4988 | 4725 | 4856 | 96.3 |
| 0.2 | 0.2 | 80 | 120 | 4800 | 4800 | 4800[a] | 90.9 |
| | | 100 | 100 | 5280 | 5280 | *5280* | *100.0* |
| | | 120 | 80 | 4800 | 4800 | 4800[b] | 90.9 |
| 0.6 | 0.5 | 80 | 120 | 3878 | 4788 | 4333 | 96.8 |
| | | 100 | 100 | 4300 | 4625 | 4463 | 99.7 |
| | | 120 | 80 | 4286 | 4230 | 4258 | 95.2 |
| | | 98[c] | 102 | 4291 | 4658 | **4474** | **100.0** |
| 0.6 | 0.4 | 80 | 120 | 4454 | 5248 | 4851 | 99.9 |
| | | 100 | 100 | 4440 | 5061 | *4750* | *97.9* |
| | | 120 | 80 | 4289 | 4520 | 4404 | 90.7 |
| | | 82[c] | 118[c] | 4457 | 5252 | **4854** | **100.0** |
| 0.6 | 0.2 | 80 | 120 | 5109 | 5968 | 5539 | 99.1 |
| | | 100 | 100 | 4720 | 5840 | 5280 | *94.5* |
| | | 120 | 80 | 4224 | 4992 | 4608 | 82.5 |
| | | 77[c] | 123[c] | 5153 | 6020 | **5587** | **100.0** |
| 0.5 | 0.4 | 80 | 120 | 4361 | 5129 | 4725 | **96.8** |
| | | 100 | 100 | 4750 | 5050 | 4900 | **99.7** |
| | | 120 | 80 | 4661 | 4608 | 4635 | **94.3** |
| | | 97[c] | 103[c] | 4742 | 5086 | 4914 | **100** |
| 0.5 | 0.2 | 80 | 120 | 4246 | 5736 | 4991 | **93.2** |
| | | 100 | 100 | 4875 | 5700 | 5288 | 98.7 |
| | | 120 | 80 | 4428 | 4881 | 4654 | 86.9 |
| | | 96[c] | 104[c] | 4932 | 5779 | **5355** | **100** |
| 0.4 | 0.2 | 80 | 120 | 4800 | 5472 | 5136 | 95.8 |
| | | 100 | 100 | 5020 | 5560 | 5290 | *98.7* |
| | | 120 | 80 | 4604 | 4795 | 4699 | 87.7 |
| | | 94[c] | 106[c] | 5072 | 5647 | **5359** | **100.0** |

[a] Maximum possible yield, because Y12 and Y21 cannot exceed Y1D being 4800
[b] Maximum possible yield, because Y12 and Y21 cannot exceed Y2D being 4800
[c] Calculated combination of U1 and U2 for maximum value of (Y12 + Y21)/2.

$e_1$= ($PhE1_{max}$ – $PhE1_{med}$)/$PhE1_{med}$ and $e_1$ = ($PhE1_{med}$ – $PhE1_{min}$)/$PhE1_{med}$ or

$e_1$ = $PhE1_{max}$/$PhE1_{med}$ – 1 and $e_1$= 1 – $PhE1_{min}$/$PhE1_{med}$.

In Figure A.4.3, $e_N$ = 70/50 -1 = 0.4, $e_P$ = 75/50 -1 = 0.5, and $e_k$ = 80/50 -1 = 0.6, while in Figure A.4.4, both $e_1$ and $e_2$ are set at 0.4. The Y12 lines represent yields obtained with U1 varying along the X-axis and with U2 fixed at 120, 100 and 80 kCNE. Y12 is higher the larger U2 is. The points of (U1 + U2 200) are maximum at 100–100, and lower at 80–120 than at 120–80 kCNE. This is seen also in Table A.4.1, at $e_1$ and $e_2$ of 0.4. For U1-U2 of 80-120, 100-100 and 120-80, the values of Y12 are 4725, 5040 and 4988.
Besides values of Y12, Table A.4.1 shows values of Y21 and of (Y12 + Y21)/2 for various combinations of $e_1$ and $e_2$ and of U1 and U2. The sum of U1 + U2 is in all cases 200 kCNE. When $e_1$ and $e_2$ have the same value, (Y12 + Y21)/2 is maximum at 100 kCNE for each U1 and U2, and Y12 is equal to Y21 displaying maximum physiological efficiency at balanced nutrition. Further Y12 at 80-120 equals Y21 at U1-U2 = 120-80 showing that Y12 and Y21 at 100-100 behave as mirrors for the yields at 80-120 and 120-80.

At small values of $e_i$, the envelopes in the graphs of yield to uptake (y = 70x and y = 30x in Figure A.4.3) are narrow and deviations of U1:U2 from 100:100 result in lower relative yields than at large values of $e_i$ (Table A.4.1). At similar U1 and U2 combinations, yields increase with decreasing values of $e_i$. When $e_1$ is larger than $e_2$, (Y12 + Y21)/2 is maximum at U1 < U2. At U1 = U2 (100-100), (Y12 + Y21)/2 is between 94 and 99% of the maximum yield, implying that at balanced nutrition physiological efficiency is close to its maximum. At all ratios of U1 to U2, Y21 is larger than Y12 if $e_2$ is smaller than $e_1$.
In the original QUEFTS model, the crop was grain maize. The values of $e_N$, $e_P$ and $e_K$ were 0.4, 0.5 and 0.6 (Janssen et al.,1992). Under those conditions yields at balanced nutrition hardly deviate from maximum yields, as demonstrated in Table A.4.1, see (Y12 + Y21)/2 for $e_1$ of 0.6 and $e_2$ of 0.5, or for $e_1$ of 0.5 and $e_2$ of 0.4, and $U_1 = U_2 = 100$.

**Table A.4.2**.
Uptake of N, P and K, in kCNE $ha^{-1}$ and as fractions of ΣU, standard deviation of the uptake fractions (SD U = SD FΣU), ratios of SD uptake to SD available amounts (SDU/SDA = SD FΣU/SD FΣA), physiological efficiency of ΣU (PhEΣU) and relative physiological efficiency of ΣU (RPhEΣU), calculated with Equation 4.12d and 4.12e and using information on yields from Table 3.2.

| Treatment | Uptake, kCNE $ha^{-1}$ N | P | K | ΣU | Fractions of ΣU, % FN | FP | FK | SD U | SDU/SDA | PhEΣU | RPhEΣU |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | *Spring-barley 1994* | | | | | | |
| N0P0K0 | 17.4 | 40.7 | 29.6 | 87.6 | 19.9 | 46.4 | 33.7 | 13.3 | 0.53 | 12.0 | 82.1 |
| N0P0K1 | 20.6 | 44.0 | 36.4 | 101.0 | 20.4 | 43.6 | 36.1 | 11.8 | 0.47 | 16.0 | 109.0 |
| N0P1K0 | 20.6 | 51.3 | 36.1 | 108.1 | 19.1 | 47.5 | 33.4 | 14.2 | 0.59 | 12.1 | 82.6 |
| N0P1K1 | 23.8 | 55.3 | 39.3 | 118.4 | 20.1 | 46.7 | 33.2 | 13.3 | 0.55 | 12.5 | 84.9 |
| NLP0K0 | 57.6 | 102.7 | 117.6 | 277.8 | 20.7 | 37.0 | 42.3 | 11.2 | 0.66 | 14.5 | 98.8 |
| NLP0K1 | 54.9 | 102.0 | 119.1 | 276.0 | 19.9 | 37.0 | 43.2 | 12.1 | 0.69 | 14.6 | 99.4 |
| NLP1K0 | 62.8 | 146.7 | 128.3 | 337.8 | 18.6 | 43.4 | 38.0 | 13.1 | 0.79 | 15.1 | 103.3 |
| NLP1K1 | 63.0 | 142.0 | 132.4 | 337.4 | 18.7 | 42.1 | 39.2 | 12.8 | 0.76 | 14.8 | 101.0 |
| NHP0K0 | 79.2 | 135.3 | 167.7 | 382.2 | 20.7 | 35.4 | 43.9 | 11.7 | 1.05 | 15.0 | 102.0 |
| NHP0K1 | 72.9 | 120.7 | 179.9 | 373.4 | 19.5 | 32.3 | 48.2 | 14.3 | 1.22 | 13.8 | 94.3 |
| NHP1K0 | 92.5 | 185.3 | 201.9 | 479.7 | 19.3 | 38.6 | 42.1 | 12.3 | 1.19 | 13.6 | 92.8 |
| NHP1K1 | 77.4 | 156.7 | 204.3 | 438.4 | 17.7 | 35.7 | 46.6 | 14.6 | 1.36 | 13.0 | 89.0 |
| | | | | | *Spring-barley 1998* | | | | | | |
| N0P0K0 | 29.0 | 62.5 | 38.1 | 129.5 | 22.4 | 48.3 | 29.4 | 13.4 | 0.77 | 15.4 | 105.3 |
| N0P0K1 | 33.6 | 68.8 | 49.3 | 151.6 | 22.1 | 45.4 | 32.5 | 11.6 | 0.61 | 16.9 | 115.1 |
| N0P1K0 | 33.0 | 74.5 | 45.4 | 152.9 | 21.6 | 48.7 | 29.7 | 13.9 | 0.72 | 15.4 | 105.2 |
| N0P1K1 | 26.7 | 59.3 | 41.2 | 127.2 | 21.0 | 46.6 | 32.4 | 12.8 | 0.66 | 16.1 | 109.9 |
| NLP0K0 | 85.1 | 141.6 | 112.2 | 338.9 | 25.1 | 41.8 | 33.1 | 8.3 | 0.98 | 15.9 | 108.6 |
| NLP0K1 | 71.7 | 123.0 | 124.0 | 318.7 | 22.5 | 38.6 | 38.9 | 9.4 | 0.80 | 16.3 | 111.0 |
| NLP1K0 | 72.9 | 150.7 | 110.3 | 333.9 | 21.8 | 45.1 | 33.0 | 11.7 | 0.96 | 16.3 | 111.2 |
| NLP1K1 | 77.5 | 154.8 | 130.1 | 362.4 | 21.4 | 42.7 | 35.9 | 10.9 | 0.87 | 15.6 | 106.7 |
| NHP0K0 | 97.9 | 138.6 | 131.6 | 368.1 | 26.6 | 37.7 | 35.8 | 5.9 | 2.06 | 15.2 | 103.9 |
| NHP0K1 | 101.3 | 141.3 | 161.9 | 404.6 | 25.0 | 34.9 | 40.0 | 7.6 | 1.25 | 14.6 | 99.3 |
| NHP1K0 | 99.6 | 161.9 | 135.0 | 396.5 | 25.1 | 40.8 | 34.0 | 7.9 | 1.15 | 14.6 | 99.7 |
| NHP1K1 | 106.1 | 185.9 | 175.0 | 467.0 | 22.7 | 39.8 | 37.5 | 9.3 | 1.37 | 13.6 | 92.8 |

| Treatment | Uptake, kCNE ha$^{-1}$ N | P | K | ΣU | Fractions of ΣU, % FN | FP | FK | SD U | SDU/SDA | PhEΣU | RPhEΣU |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | *Sugar-beets 1999* | | | | | |
| N0P0K0 | 58 | 107 | 196 | 361 | 16.1 | 29.7 | 54.2 | 19.3 | 0.82 | 19.8 | 68.8 |
| N0P0K1 | 70 | 122 | 254 | 446 | 15.7 | 27.4 | 56.9 | 21.3 | 0.87 | 17.9 | 62.1 |
| N0P1K0 | 81 | 157 | 258 | 497 | 16.3 | 31.7 | 52.0 | 17.9 | 0.80 | 19.5 | 67.8 |
| N0P1K1 | 59 | 131 | 229 | 419 | 14.0 | 31.2 | 54.8 | 20.5 | 0.90 | 17.7 | 61.5 |
| NLP0K0 | 166 | 117 | 421 | 703 | 23.5 | 16.6 | 59.9 | 23.2 | 1.45 | 20.2 | 70.0 |
| NLP0K1 | 149 | 131 | 462 | 741 | 20.1 | 17.6 | 62.3 | 25.1 | 1.42 | 16.7 | 57.9 |
| NLP1K0 | 179 | 243 | 450 | 872 | 20.5 | 27.9 | 51.6 | 16.2 | 1.04 | 17.8 | 61.9 |
| NLP1K1 | 162 | 238 | 485 | 885 | 18.3 | 26.9 | 54.8 | 19.1 | 1.17 | 17.6 | 61.0 |
| NHP0K0 | 280 | 185 | 659 | 1123 | 24.9 | 16.4 | 58.6 | 22.3 | 2.09 | 13.0 | 45.0 |
| NHP0K1 | 302 | 177 | 719 | 1198 | 25.2 | 14.8 | 60.1 | 23.7 | 1.90 | 15.1 | 52.5 |
| NHP1K0 | 244 | 288 | 513 | 1045 | 23.3 | 27.6 | 49.1 | 13.8 | 1.40 | 14.7 | 50.9 |
| NHP1K1 | 285 | 283 | 650 | 1218 | 23.4 | 23.3 | 53.4 | 17.3 | 1.61 | 12.9 | 44.9 |
| | | | | | | *Potatoes 1995* | | | | | |
| N0P0K0 | 16.8 | 35.3 | 31.1 | 83.2 | 20.2 | 42.5 | 37.4 | 11.7 | 0.56 | 26.2 | 109.9 |
| N0P0K1 | 20.8 | 46.7 | 38.8 | 106.3 | 19.6 | 43.9 | 36.5 | 12.5 | 0.59 | 24.7 | 103.4 |
| N0P1K0 | 27.6 | 75.3 | 48.6 | 151.5 | 18.2 | 49.7 | 32.1 | 15.8 | 0.71 | 22.5 | 94.5 |
| N0P1K1 | 29.5 | 86.0 | 56.8 | 172.3 | 17.1 | 49.9 | 33.0 | 16.4 | 0.74 | 22.4 | 93.8 |
| NLP0K0 | 136.4 | 117.3 | 97.3 | 351.0 | 38.9 | 33.4 | 27.7 | 5.6 | 1.88 | 23.6 | 99.1 |
| NLP0K1 | 137.2 | 114.0 | 111.5 | 362.7 | 37.8 | 31.4 | 30.7 | 3.9 | 2.32 | 23.8 | 99.9 |
| NLP1K0 | 163.1 | 172.7 | 111.4 | 447.1 | 36.5 | 38.6 | 24.9 | 7.4 | 1.58 | 23.3 | 97.8 |
| NLP1K1 | 162.0 | 164.7 | 132.1 | 458.7 | 35.3 | 35.9 | 28.8 | 3.9 | 1.86 | 23.3 | 97.9 |
| NHP0K0 | 196.1 | 156.0 | 134.9 | 487.0 | 40.3 | 32.0 | 27.7 | 6.4 | 0.42 | 21.6 | 90.5 |
| NHP0K1 | 167.4 | 128.0 | 133.5 | 428.9 | 39.0 | 29.8 | 31.1 | 5.0 | 0.37 | 22.1 | 92.7 |
| NHP1K0 | 210.0 | 182.0 | 131.1 | 523.1 | 40.1 | 34.8 | 25.1 | 7.6 | 0.57 | 21.6 | 90.5 |
| NHP1K1 | 228.6 | 186.0 | 171.9 | 586.5 | 39.0 | 31.7 | 29.3 | 5.0 | 0.44 | 20.7 | 87.0 |

**Table A.4.3**.
Amounts of available N, P and K in soil and input, in kCNE ha$^{-1}$ and as fractions of their sum (ΣA), standard deviation (SD A = SD FΣA) of the fractions, agronomic use efficiency of ΣA (AEΣA) and relative agronomic use efficiency of ΣA (RAEΣA), as calculated with Equation 12c. Values of SA and IA were calculated on the basis of information from Tables 3.1 and 3.11 and on values of CFP and CFK presented in Table 4.2.

| Treatment | Available, kCNE ha$^{-1}$ | | | | Fractions of ΣA, % | | | | AEΣA | RAEΣA |
|---|---|---|---|---|---|---|---|---|---|---|
| | N | P | K | ΣA | FN | FP | FK | SD A | | |
| *Spring-barley 1994* | | | | | | | | | | |
| N0P0K0 | 24 | 135 | 202 | 361 | 6.6 | 37.4 | 55.9 | 24.9 | 2.92 | 19.9 |
| N0P0K1 | 24 | 135 | 209 | 368 | 6.5 | 36.7 | 56.8 | 25.3 | 4.39 | 29.9 |
| N0P1K0 | 24 | 182 | 202 | 408 | 5.9 | 44.6 | 49.5 | 23.9 | 3.21 | 21.9 |
| N0P1K1 | 24 | 182 | 209 | 415 | 5.8 | 43.9 | 50.3 | 24.1 | 3.56 | 24.2 |
| NLP0K0 | 65 | 135 | 202 | 402 | 16.2 | 33.6 | 50.2 | 17.0 | 10.01 | 68.2 |
| NLP0K1 | 65 | 135 | 209 | 409 | 15.9 | 33.0 | 51.1 | 17.6 | 9.84 | 67.1 |
| NLP1K0 | 65 | 182 | 202 | 449 | 14.5 | 40.5 | 45.0 | 16.5 | 11.39 | 77.7 |
| NLP1K1 | 65 | 182 | 209 | 456 | 14.3 | 39.9 | 45.8 | 16.8 | 10.97 | 74.8 |
| NHP0K0 | 106 | 135 | 202 | 443 | 23.9 | 30.5 | 45.6 | 11.1 | 12.91 | 88.0 |
| NHP0K1 | 106 | 135 | 209 | 450 | 23.6 | 30.0 | 46.4 | 11.8 | 11.48 | 78.3 |
| NHP1K0 | 106 | 182 | 202 | 490 | 21.6 | 37.1 | 41.2 | 10.3 | 13.33 | 90.9 |
| NHP1K1 | 106 | 182 | 209 | 497 | 21.3 | 36.6 | 42.0 | 10.7 | 11.51 | 78.5 |
| *Spring-barley 1998* | | | | | | | | | | |
| N0P0K0 | 44 | 147 | 138 | 330 | 13.3 | 44.7 | 42.0 | 17.4 | 6.1 | 41.4 |
| N0P0K1 | 44 | 147 | 179 | 370 | 11.9 | 39.8 | 48.3 | 19.0 | 6.9 | 47.2 |
| N0P1K0 | 44 | 183 | 138 | 365 | 12.0 | 50.0 | 37.9 | 19.4 | 6.5 | 44.1 |
| N0P1K1 | 44 | 183 | 179 | 406 | 10.9 | 45.1 | 44.1 | 19.5 | 5.1 | 34.5 |
| NLP0K0 | 84 | 147 | 138 | 370 | 22.7 | 39.8 | 37.5 | 9.3 | 14.6 | 99.6 |
| NLP0K1 | 84 | 147 | 179 | 410 | 20.5 | 35.9 | 43.6 | 11.8 | 12.7 | 86.4 |
| NLP1K0 | 84 | 183 | 138 | 405 | 20.7 | 45.1 | 34.2 | 12.2 | 13.4 | 91.6 |
| NLP1K1 | 84 | 183 | 179 | 446 | 18.9 | 41.0 | 40.1 | 12.5 | 12.7 | 86.8 |
| NHP0K0 | 124 | 147 | 138 | 410 | 30.3 | 35.9 | 33.8 | 2.9 | 13.7 | 93.4 |
| NHP0K1 | 124 | 147 | 179 | 450 | 27.6 | 32.7 | 39.7 | 6.1 | 13.1 | 89.4 |
| NHP1K0 | 124 | 183 | 138 | 445 | 27.9 | 41.0 | 31.1 | 6.9 | 13.0 | 88.8 |
| NHP1K1 | 124 | 183 | 179 | 486 | 25.6 | 37.6 | 36.8 | 6.7 | 13.1 | 89.2 |

| Treatment | Available, kCNE ha$^{-1}$ N | P | K | ΣA | Fractions of ΣA, % FN | FP | FK | SD A | AEΣA | RAEΣA |
|---|---|---|---|---|---|---|---|---|---|---|
| *Sugar-beets 1999* | | | | | | | | | | |
| N0P0K0 | 80.0 | 322.2 | 500.0 | 902.2 | 8.9 | 35.7 | 55.4 | 23.4 | 7.9 | 27.6 |
| N0P0K1 | 80.0 | 322.2 | 545.6 | 947.8 | 8.4 | 34.0 | 57.6 | 24.6 | 8.4 | 29.2 |
| N0P1K0 | 80.0 | 488.9 | 500.0 | 1068.9 | 7.5 | 45.7 | 46.8 | 22.4 | 9.1 | 31.5 |
| N0P1K1 | 80.0 | 488.9 | 545.6 | 1114.4 | 7.2 | 43.9 | 49.0 | 22.8 | 6.7 | 23.1 |
| NLP0K0 | 179.0 | 322.2 | 500.0 | 1001.2 | 17.9 | 32.2 | 49.9 | 16.1 | 14.2 | 49.2 |
| NLP0K1 | 179.0 | 322.2 | 545.6 | 1046.8 | 17.1 | 30.8 | 52.1 | 17.6 | 11.8 | 41.0 |
| NLP1K0 | 179.0 | 488.9 | 500.0 | 1167.9 | 15.3 | 41.9 | 42.8 | 15.6 | 13.3 | 46.2 |
| NLP1K1 | 179.0 | 488.9 | 545.6 | 1213.4 | 14.8 | 40.3 | 45.0 | 16.3 | 12.8 | 44.5 |
| NHP0K0 | 278.0 | 322.2 | 500.0 | 1100.2 | 25.3 | 29.3 | 45.4 | 10.7 | 13.2 | 45.9 |
| NHP0K1 | 278.0 | 322.2 | 545.6 | 1145.8 | 24.3 | 28.1 | 47.6 | 12.5 | 15.8 | 54.9 |
| NHP1K0 | 278.0 | 488.9 | 500.0 | 1266.9 | 21.9 | 38.6 | 39.5 | 9.9 | 12.1 | 42.0 |
| NHP1K1 | 278.0 | 488.9 | 545.6 | 1312.4 | 21.2 | 37.3 | 41.6 | 10.7 | 12.0 | 41.6 |
| *Potatoes 1995* | | | | | | | | | | |
| N0P0K0 | 31.0 | 153.3 | 140.6 | 325.0 | 9.5 | 47.2 | 43.3 | 20.7 | 6.7 | 28.2 |
| N0P0K1 | 31.0 | 153.3 | 167.1 | 351.4 | 8.8 | 43.6 | 47.5 | 21.3 | 7.5 | 31.3 |
| N0P1K0 | 31.0 | 186.7 | 140.6 | 358.3 | 8.7 | 52.1 | 39.3 | 22.3 | 9.5 | 40.0 |
| N0P1K1 | 31.0 | 186.7 | 167.1 | 384.8 | 8.1 | 48.5 | 43.4 | 22.0 | 10.0 | 42.0 |
| NLP0K0 | 168.0 | 153.3 | 140.6 | 462.0 | 36.4 | 33.2 | 30.4 | 3.0 | 18.0 | 75.3 |
| NLP0K1 | 168.0 | 153.3 | 167.1 | 488.4 | 34.4 | 31.4 | 34.2 | 1.7 | 17.7 | 74.2 |
| NLP1K0 | 168.0 | 186.7 | 140.6 | 495.3 | 33.9 | 37.7 | 28.4 | 4.7 | 21.0 | 88.3 |
| NLP1K1 | 168.0 | 186.7 | 167.1 | 521.8 | 32.2 | 35.8 | 32.0 | 2.1 | 20.5 | 86.1 |
| NHP0K0 | 305.0 | 153.3 | 140.6 | 599.0 | 50.9 | 25.6 | 23.5 | 15.3 | 17.5 | 73.6 |
| NHP0K1 | 305.0 | 153.3 | 167.1 | 625.4 | 48.8 | 24.5 | 26.7 | 13.4 | 15.1 | 63.6 |
| NHP1K0 | 305.0 | 186.7 | 140.6 | 632.3 | 48.2 | 29.5 | 22.2 | 13.4 | 17.8 | 74.8 |
| NHP1K1 | 305.0 | 186.7 | 167.1 | 658.8 | 46.3 | 28.3 | 25.4 | 11.3 | 18.5 | 77.5 |

# Chapter 5

# Final observations and conclusions of the long-term soil fertility study in the former sea-bottom

## 5.1. Original and subsequent research questions and answers

The basic research questions of this long-term experiment were how long it would take before crop performance suffered from shortages in N, P and K, and whether different crops behaved and responded similarly to applied nutrients. The initial (internal) reports on the experiment were restricted to statistical analysis of the effects of N, P and K application on yields and revealed only effects of N (Slangen & Menkveld, 1982). Ratios of yields obtained with treatments N0 and N1, P0 and P1, and K0 and K1 were hardly changing over time (Janssen & Menkveld, 1998). These documents did not yet give final answers to the basic questions. The answers described in Chapter 2 were: no responses to K were found, highly significant responses to N, and irregular responses to P for sugar-beets, potatoes and spring-barley, but never for silage maize and winter-wheat. The study also showed that yields were strongly related to rainfall in the preceding winter months, especially when no N was applied. The results of Chapter 2 led to the questions whether the poor response to P and K was caused by unavailability of applied P and K - due to fixation in the soil or leaching from the soil - or by more than sufficient provision of P and K by the soil alone, and how the differences among the crops could be explained. Chemical crop analysis (Chapter 3) revealed that input P and K could easily be taken up by the crops, but that this extra uptake did not result in extra yield. The amounts of P and K taken up from the soil as well as from input were strongly related to the uptake of N. If no N was applied, P and K uptake efficiencies were very low leaving a major part of soil available P and K unused. Hence, next question was how the use efficiencies of N, P and K could be improved and optimized. In Chapter 4, in addition to uptake efficiency, another two types of nutrient use efficiency were introduced (physiological use efficiency; agronomic use efficiency), as well as the concept of crop nutrient equivalent (CNE). They together formed a set of tools to build a framework for the assessment of the requirements of available N, P and K for specified target yields (water-limited crop production) at optimum NPK use efficiency (= maximum yield per kCNE of available N + P + K). Equal supplies of available N, P and K, expressed in CNE, proved to result in maximum or near maximum nutrient use efficiency.

## 5.2. Available nutrients in soil and input

The maximum amount of a nutrient a crop takes up - when that nutrient is the most limiting growth factor and all other growth factors are optimal - was taken as the quantity of the nutrient in soil (SA) and input (IA) that is available (Section 3.2.3). N was by far the most limiting growth factor. Following this definition, Figure 3.1. shows the amount of available nitrogen in soil (SAN) and input (IAN) in this long-term experiment. It was more difficult to determine available P (SAP and IAP) and K (SAK and IAK), as these nutrients were not yield limiting. The best option was to estimate them in plots receiving N input.

SAN proved to depend on crop species (Table 3.11) and on rainfall in preceding winter months. The influence of crop species must be ascribed to differences among crops in rooting depth, root density and growth duration. These factors were underlying the SAN sequence in the order: sugar-beets 1999 > spring-barley 1998 > potatoes 1995 > spring-barley 1994. The sequence of SAP was the same, but that of SAK differed: sugar-beets 1999 > potatoes 1995 > spring-barley 1994 > spring-barley 1998, reflecting the large K demand by potato, and a decrease in soil K availability between 1994 and 1998 (Section 3.4.4). Soil available P and K (SAP and SAK) or more precisely, the uptakes of soil P and soil K (SUP and SUK) were related to the uptake of N, (UN in Figures 3.3 and 3.4), and hence to the input of N (IN in Figure 3.1). A number of the values of $UN_m$ required for maximum SUP and SUK (Tables 3.7 and 3.10) were outside the ranges of observed UN and some were negative.
The uptake of P and K from the soil alone was more than sufficient for the required uptake at balanced NPK nutrition for water-limited yields of spring-barley and sugar-beets but not of potatoes (Table 4.8), as shown in Section 5.3.

## 5.3. Calculation of maximum yields attainable with the uptake of P and K from the soil alone

The outcomes of Chapters 3 and 4 make it possible to calculate at which uptake of N (UN) the uptake of P from the soil alone (SUP) is greater than or equal to the required P uptake for balanced ratios of UN to UP ($UP_{bal}$). Similarly, one can calculate at which UN the uptake of K from the soil alone (SUK) is greater than or equal to the required K uptake for balanced ratios of UN to UK ($UK_{bal}$). The uptake at balanced nutrition is equal to $Y/PhE_{med}$ (Section A.4.1). It follows from Section A.4.3 and Equations A.4.1 and A.4.1b, that at balanced nutrition:

$$UP_{bal}/UN_{bal} = [Y/PhEP_{med}]/[Y/PhEN_{med}] = PhEN_{med}/PhEP_{med} = CFP, \text{ and}$$
$$UK_{bal}/UN_{bal} = [Y/PhEK_{med}]/[Y/PhEN_{med}] = PhEN_{med}/PhEK_{med} = CFK.$$

In other words, for balanced nutrition, UP should equal UN · CFP, and UK should be equal to UN · CFK (CFP and CFK are conversion factors of P and K), or generally

$$U_{i\ bal} = UN_{bal} \cdot CF_i \qquad \text{(Eq. 5.1)}$$

Figures 3.3 and 3.4 present equations to calculate SUP and SUK in relation to UN for the curves at P0 and K0, respectively. The general form is

$$y = a \cdot x^2 + b \cdot x + c \qquad \text{(Eq. 5.2)}$$

In Equation 5.2, y = SUP or SUK, and x = UN.
When the outcomes of Equations 5.1 and 5.2 are equal, x in Equation 5.2 represent $UN_{bal}$ , and it holds:

$$a \cdot x^2 + b \cdot x + c = UN_{bal} \cdot CF \text{ or}$$
$$a \cdot x^2 + (b - CF) \cdot x + c = 0 \qquad \text{(Eq. 5.3)}$$

There are two solutions for x (= $UN_{bal}$ ) in Equation 5.3

$$x = [- (b - CF) + SQRT\{(b - CF)^2 - 4 \cdot a \cdot c \}]/(2 \cdot a) \qquad \text{(Eq. 5.4a)}$$
or
$$x = [- (b - CF) - SQRT\{(b - CF)^2 - 4 \cdot a \cdot c \}]/(2 \cdot a) \qquad \text{(Eq. 5.4b)}$$

Once x is known, y = SUP = $UP_{bal}$, or y = SUK = $UK_{bal}$ can be found with Equations 5.1 or 5.2. The corresponding yield at balanced NPK ($yield_{bal}$) is:

$$yield_{bal} = x \cdot PhEN_{med} \qquad \text{(Eq. 5.5a)}$$
or if y stands for SUP: $yield_{bal} = y \cdot PhEP_{med}$ (Eq. 5.5b)
or, if y stands for SUK: $yield_{bal} = y \cdot PhEK_{med}$ (Eq. 5.5c)

The difference between the uptake of soil P and the required balanced uptake of UP, and the difference between the uptake of soil K and the required balanced uptake of UK are equal to:

$$SUP - UP_{bal} = a \cdot UN^2 + b \cdot UN + c - UN_{bal} \cdot CFP, \text{ and}$$
$$SUK - UK_{bal} = a \cdot UN^2 + b \cdot UN + c - UN_{bal} \cdot CFK$$

Figure 5.1 shows these calculated differences in relation to the uptake of N (from soil and input). As long as SUP or SUK is greater than $UP_{bal}$ or $UK_{bal}$, no positive response in yield to P or K input is to be expected. It is obvious that potatoes were weakest in absorbing P and K from the soil. Potato tuber DM yields would be not more than 4 to 5 Mg if no K or P would be applied (Table 5.1). Especially the large potato demand of K (about 1.5 times the demand of N) influences this picture. The weak absorption of soil P and K in combination with the relatively strong requirements of potato explain the rather exceptional position of this crop in this long-term experiment on the bottom of the former 'Zuyderzee'.

## 5.4. Chemical soil analysis and soil nutrient pools

It is a pity that the number of soil analytical data acquired in this long-term experiment was very limited (Table 2.2). It would have been interesting to find out whether the continuous withdrawal of P and K shows up in diminishing values of soil chemical parameters. 'Literal translation' of soil analytical data, such as P-water and K-HCl to the field/crop situations is not acceptable. Nevertheless, such a conversion may be illustrative. A topsoil of 25 cm has a volume of $2.5 \cdot 10^6$ $dm^3$. With a bulk density of 1.2 kg $dm^{-3}$, the topsoil mass is $3 \cdot 10^6$ kg $ha^{-1}$. Hence, the initial values of P-water and K-HCl in Table 2.2 correspond to 28.4 kg $ha^{-1}$ P and 423 kg $ha^{-1}$ K. Surprisingly enough, the value of 28 kg $ha^{-1}$ P is in the same order of magnitude as SUP presented in Table 5.1, and as 'Available P at P0' in Table 3.6. Likewise, the value of 423 kg $ha^{-1}$ K is in the same order of magnitude as SUK in Table 5.1, and as 'Available K at K0' in Table 3.9. The data in Table 2.2, however, refer to the year of 1975 while the data in Tables 3.6, 3.9 and 5.1 are from the years 1994 to 1999. How to explain that the laboratory data of 1975 give approximately the same answers as the crop uptake in the field 20 to 25 years later? A short discussion about soil nutrient pools may be helpful.

Many chemical methods for P as well for K, developed in the last century, claim to represent 'available soil P' and 'available soil K'. On the other hand, some more laborious methods distinguish conceptual soil pools of increasing stability: very labile < labile < medium < stable < very stable/inert (e.g. Selim et al. 1976; Hedley et al. 1982), of which the very labile and labile pools represent 'available soil P' and 'available soil K'. Figure 5.2 gives a simplified overview of inputs, internal flows and outputs of nutrients to and from (only) three conceptual soil pools. During every growing season, the sizes of the labile and medium pool decrease because the crops withdraw of P and K (via the soil solution) from these pools. Partly during, but mainly after the growth period, the more labile pools are 'refilled' from the more stable pools. This may continue until the stable pool becomes too small to replenish the medium pool. Next, the medium pool becomes too small to replenish the labile pool, resulting in a decreasing uptake by the crop. Nutrient inputs prevent such a decline of the soil nutrient pools.

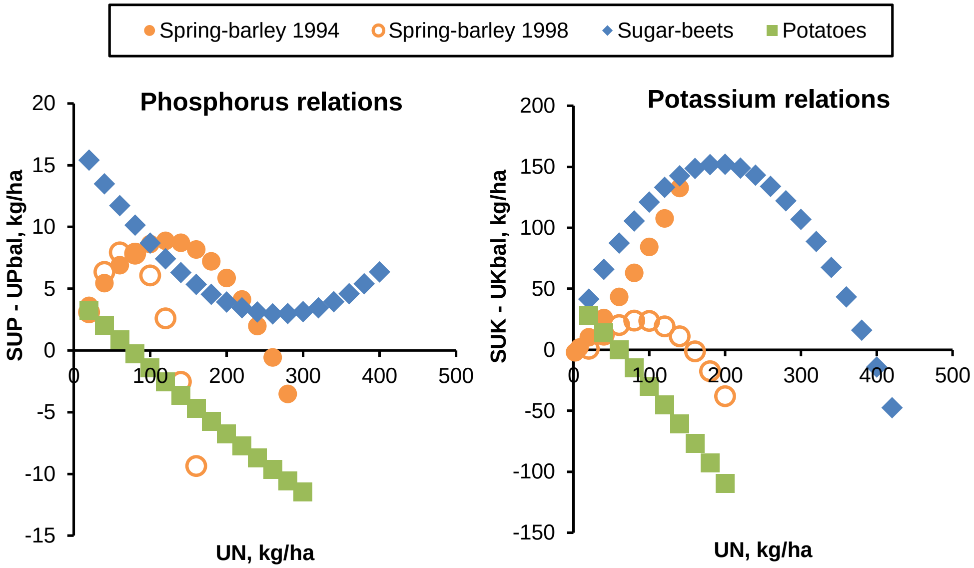


**Fig. 5.1.** Relation between calculated differences SUP - $UP_{bal}$ (left-hand side) and SUK - $UK_{bal}$ (right-hand side) and the uptake of N (from soil and input). SUP and SUK stand for the uptake from the soil alone of P and K. $UP_{bal}$ and $UK_{bal}$ signify the uptake of P and K required for balanced NP and NK uptake (see Section 5.3).

**Table 5.1.**
Calculated maximum or minimum yields attainable with uptake from the soil alone of P (SUP) or of K (SUK), corresponding SUP or SUK, and uptake of N (from soil and input) for balanced NP or NK uptake. All data in kg ha$^{-1}$. See Figure 5.1.

| Crop | Phosphorus relations | | | Potassium relations | | |
|---|---|---|---|---|---|---|
| | Yield | SUP | UN | Yield | SUK | UN |
| Spring-barley 1994 | 11259[a] | 38.4[a] | 256[a] | 221[c] | 3.5[c] | 5[c] |
| Spring-barley 1998 | 5764 | 19.6 | 131 | 6958 | 110.7[a] | 158[a] |
| Sugar-beets 1999 | insoluble[b] | insoluble[b] | insoluble[b] | 33818[a] | 351.9[a] | 391[a] |
| Potatoes 1995 | 5366 | 11.3 | 75 | 4264 | 92.5 | 60 |

[a] Beyond observed values
[b] SUP is always greater than required balanced UP because the relation between UP and UN for P0 is a minimum parabola (see Figure 3.3). The minimum value of (SUP – $UP_{bal}$) is 2.96 kg ha$^{-1}$ and the corresponding values of yield, SUP and UN are 23355, 24.3 and 270 kg ha$^{-1}$, respectively.
[c] Beyond UN = 5 kg ha$^{-1}$, SUK is always greater than required balanced UK (see Figure 5.1) because the relation between UK and UN for K0 is a minimum parabola (see Figure 3.4).

Not included in Figure 5.1 is the soil solution in between labile pool and crop, and in between medium pool and crop. The flows of nutrient losses by leaching and gaseous losses from the soil solution, and by erosion from all pools are neither included, nor are inputs by deposition indicated. Erosion was not an issue in the flat area of APM. Leaching of N and K probably occurred via the drains in wintertime, roughly from October to April, but it was not measured. The inputs were estimated at 50 kg N, 1 kg P and 10 kg K per ha per year (CBS, PBL, Wageningen UR, 2016). The depositions of P and K were small and practically negligible compared to the soil available supplies of about 25 kg P and 275 kg K per ha (Table 4.8). The deposition of N, however, was significant compared to the soil available supply of 40 to 75 kg $ha^{-1}$. It likely contributed considerably to the maintenance of the control yields (N0P0) during the 28 years of the experiment (Figure 27).

Depending on the chemical composition of the input nutrient source, input nutrients move to one or more soil pools. The potassium fertilizers used at APM are very soluble and go to the labile pool initially, but may move to the medium pool later on. The phosphorus fertilizer used also goes to the labile pool for the major part, but a fraction, estimated at 20 percent, does hardly dissolve and becomes part of the stable pool. Usually there is sufficient time to replenish the labile pools before the next crop growing period, but in very intensive cropping systems, such as the one with three rice crops per year, the time between two successive crops may be too short (Hoa, 2003) to restore the labile pool.

The analytical methods mentioned in Table 2.2 refer to a very labile soil-P pool (P-water), and to a labile soil K pool (K-HCl). Unfortunately, no other, more stable, pools were analysed in the APM soil. Such analyses require a lot of time and funds but there is no need to repeat them often, whereas labile or very labile pools require more frequent or even annual analyses. It is difficult to find appropriate laboratory methods for the determination of ‘medium’ pools (Hoa, 2003). It is easier to determine the sum of the medium and stable pool as the difference between total P or K and labile P or K. The ratio of total P to labile P (or total K to labile K) serves as an indication of sustainability of agroecosystems (Janssen, 1999). A simple model comprising only two soil K pools, labile K and ‘recalcitrant K’ (total minus labile), proved satisfactory to predict various K management scenarios under intensive rice cropping in the Mekong Delta, Vietnam (Hoa et al. 2006). In the present study, such a simple model could have approximately predicted for how long the soil supplies of P and K would remain adequate. It would have saved a lot of work, as follows from a simple calculation. Total P likely was originally (i.e. in 1975) between 600 and 1000 mg kg-1 (Van Wijk et al., 2014) corresponding to 1800 to 3000 kg ha-1 in a topsoil of $3 \cdot 10^6$ kg ha-1. This quantity is 90 to 150 times the ‘average’ crop P uptake at NHP0 of 20 kg ha-1 (Table 3.6).

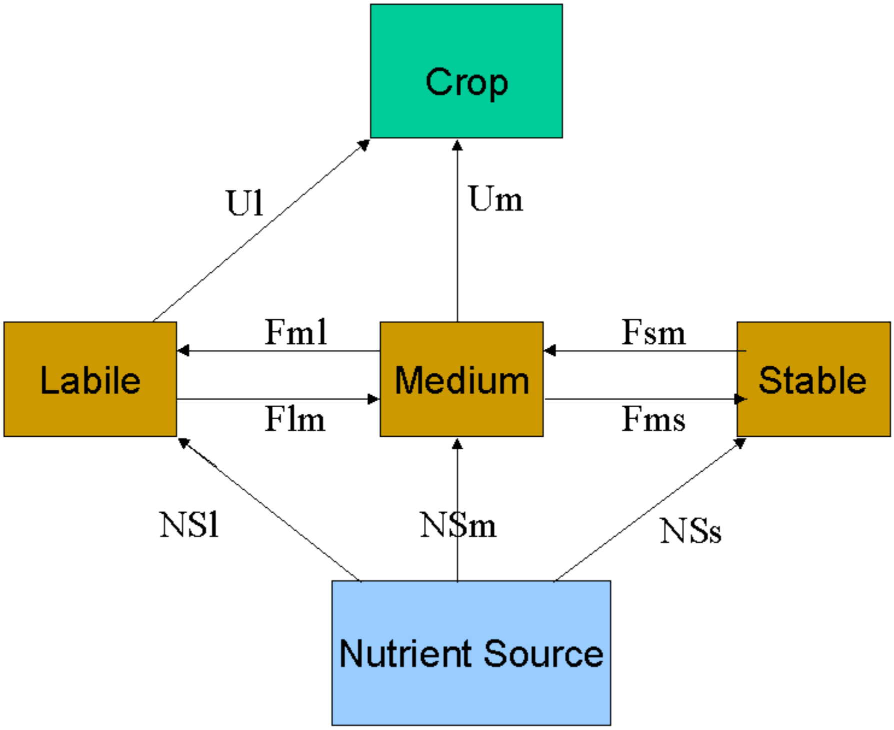


**Fig. 5.2.** Simplified scheme of the allocation of added nutrients to soil pools, and nutrient uptake by the crop from soil pools. NS stands for Nutrient Source, F for soil internal flow, U means uptake by crop (via soil solution). The characters along the arrows indicate the direction of the flows from and to the indicated pools. The lower case letters l, m and s stand for labile, medium and stable. Not included are nutrient losses, nutrient deposition and soil solution (see Section 5.4) Source: Janssen 2002.

Until present, 2017, P input by farmers often is greater than P output. In such cases, the flows in Figure 5.2 move from labile to stable pools. Soil P increases, the more stable pools stronger than the more labile pools (Van Middelkoop et al., 2016). It takes considerable time to lower soil P (Van der Salm et al., 2008), similar to the experience in this long-term experiment.

## 5.5 Variability and (un)certainty

Statistical analyses were carried out on the yield data of each individual year testing the main effects of replicates, N, P and K, and NP interaction (Chapter 2). The many regression equations calculated in Chapters 3 and 4 usually had high R-square values giving confidence to the underlying relationships. Nevertheless, the derived values of optimum x and maximum y values (Tables 3.4, 3.5, 3.7, 3.10) were not always reliable because optimum x was outside the range of observed x values. This weakened the estimation of soil available P and K. Sometimes the coefficient of the quadratic term in the equations was not negative, making calculation of optimum x impossible. The procedure followed to estimate available nutrients in soils and inputs (Equations 3.4a – 3.4e) had its strong and weak points because the calculations were based on four data per case only.

For the estimation of minimum and maximum physiological use efficiencies, data from literature of 30 and more years old were used for want of better information. The results obtained at APM fitted well within the envelopes formed by these extremes (Figures 4.1, 4.2, 4.3). The corresponding conversion factors used for the calculation of crop nutrient equivalents (CNE) had realistic values, allowing the assessment of balanced NPK nutrition and balanced NPK supplies. Valuating the observed APM nutrient use efficiencies by comparing them to independent external values for relative uptake, physiological and agronomic efficiency, further extended the usefulness of the followed procedures.

## 5.6 Synthesis of results and conclusions

1. Yields responded on average by 89% to N application, by 8% to P application and never to K application. Table A.2.1.
2. Yields varied from year to year in the long-term experiment. A major cause of the variation among years was the difference in preceding winter rainfall. Figure A.2.1 and Figure 2.2. Adjusting yields to an average winter rainfall of 305 mm reduced the average coefficient of variation from 16.6 to 7.6%. Table A.2.1 and Table 2.4.
3. Adjusted yields did not decline during the 28 years of the experiment, even not when no N was applied. Table 2.6. The responses to N and P by sugar-beets and potatoes increased over time, likely because more productive varieties were used.
4. The supply of available nutrients was estimated as the maximum uptake of that nutrient when it is by far the most limiting growth factor. Section 3.2.3.
5. The assessment of available nutrients in ‘soil plus input’ via maximum uptake by the crop gave a better insight into the consequences of nutrients use than considering only chemical soil data and fertilizer nutrients and yields. Chapter 2. Section 3.4.2. Section 5.4
6. The steady state of soil available N was ascribed for a considerable part to atmospheric N deposition. Section 5.4.

7. The estimated soil supplies of available P were a function of N uptake and crop type. Figure 3.3. Table 3.6. The apparent steady state of soil available P was ascribed to a large stable soil P pool. Figure 5.2. Section 5.4.
8. The estimated soil supplies of available K were a function of N uptake and crop type. Figure 3.4. Table 3.9. Despite a small decrease between 1994 and 1998 in soil K uptake (SUK) by spring-barley (Figure 3.6), in 1998 SUK was still more than needed for balanced NK nutrition. Figure 5.1.
9. For the evaluation of the balance among N, P and K, their quantities were expressed in crop nutrient equivalents (CNE). Section 4.2.3. Appendix 4, Section A.4.3.
10. Nutrient use efficiency was distinguished into uptake efficiency, physiological efficiency, and agronomic efficiency. Sections 3.2.5, 4.2.2, 4.2.4 and 4.2.5.
11. Maximum uptake and agronomic use efficiencies of the sum of N, P and K were obtained at (near) equal supplies of available N, P and K expressed in crop nutrient equivalents. Figure 4.5. Table A.4.1. Table A.4.3.
12. The relationships established in this study were used to calculate the required inputs for balanced NPK supplies at any target yield. Section 4.3.7. Table 4.8.
13. A prudent estimate is that it takes 90 to 150 years to deplete the P supplies in this marine clay soil. Section 5.4.
14. The stronger yield response to P application by potato than by spring-barley and sugar-beets was ascribed to the weak capacity of this crop to absorb sufficient P from the soil alone. Table 3.2. Table 3.6. Table A.3.1.
15. The stronger yield response to K application by potato than by spring-barley and sugar-beets was ascribed to the large K requirements of this crop, as reflected in its great CFK value and relative dilution. Table 4.2. Figure 4.3. Table 4.6.
16. The absence of a response to P and K application by spring-barley and sugar-beets was not caused by losses of input P and K from the soil or by fixation of input P and K onto or into soil minerals, but by more than sufficient supplies of P and K in the soil. Figure 5.1.

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