Solutions to Improve Fertilizer Nutrient Use Efficiency

肥料养分高效利用策略

何 萍 主编

中国农业科学技术出版社

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Proceedings of the International Symposium on Improvement of Nutrient Use Efficiency under Zero Growth of Chemical Fertilizers

化肥零增长下养分高效利用国际学术研讨会论文集

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《肥料养分高效利用策略》

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前　言

大量实践证明，肥料在保障我国粮食安全中发挥了重要作用。然而，近年来我国化肥过量和不合理施用问题严重，单位面积化肥用量是世界平均水平的3倍以上，由此导致肥料利用率低，引起水体富营养化、温室气体增排、土壤酸化等环境问题，直接影响到我国农业增产和农民增收，其生态环境效应也引起世界的广泛关注。因此，如何高效利用肥料养分、提高肥料利用率，是保障国家粮食安全、生态环境安全和农田可持续利用的重大国家需求。

2015年农业部提出，到2020年中国农业要实现化肥用量零增长，科技部也先后启动了973计划和国家重点研发计划试点专项，开展化肥“减施增效”综合技术研发。为借鉴发达国家化肥“减施”的成功经验，交流肥料养分高效利用的最新进展，国际植物营养研究所（IPNI）、中国农业科学院农业资源与农业区划研究所、中国植物营养与肥料学会等单位于2016年3月16—18日在北京联合组织召开了“化肥零增长下养分高效利用国际学术研讨会”，旨在提出化肥科学“减施”和提高肥料利用率的对策与途径，助力国家化肥零增长计划的实现。来自美国、英国、德国、加拿大、澳大利亚、印度、法国、意大利等国外专家和国内110个不同单位的300余名代表参加了此次会议。与会代表就粮食作物、经济作物、蔬菜、果树养分管理以及新型肥料与施肥技术、肥料养分高效利用策略等6个方面进行了深入交流和研讨。

本书收录了研究论文、摘要和综述共56篇，内容涉及粮食作物、经济作物、蔬菜、果树养分管理以及新型肥料与施肥技术、肥料养分高效利用策略等方面的研究，反映了近年来国际上作物养分管理和高效施肥领域的最新研究成果。

“化肥零增长下养分高效利用国际学术研讨会”得到了农业部、中国农业科学院、国际肥料工业协会（IFA）和加拿大钾肥公司（Canpotex）的大力支持。特别感谢IPNI所长Terry Roberts和副所长Adrian Johnston博士为此次会议的成功召开所作出的努力，以及IPNI中国项目部全体同仁的辛勤付出。感谢为本书的研究成果作出贡献的所有研究人员。感谢中国农业科学技术出版社的大力支持。

现将此书奉献给读者，希望能够进一步推动作物养分管理和肥料高效利用的技术进步。在本书编辑出版过程中，我们力求数据可靠、分析透彻、论证全面、观点客观，但可能存在疏漏和不足之处，敬请读者批评指正。

2016年9月

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第 1 章
Chapter 1

粮食作物养分管理
Nutrient Management for Cereal Crops

Prospects for Achieving Higher Nutrient Use Efficiency as Yields Increase in Cereal Production Systems

Tony J. Vyn
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Introduction

As we look to the future, people in nations around the world share the same concerns about increasing cereal production (because it is, and will continue to be, the essential food staple of an expanding population) while also reducing nutrient losses to the environment. Despite considerable evidence to the contrary, critics abound in inferring that higher cereal yields are only achieved by ever higher nutrient application rates per unit area, and ever higher risks of nutrient contamination of our water and air resources. Such critics may be well-intentioned in their environmental concerns, but they also need to hear "the rest of the story" from both plant scientists and soil scientists. That reassuring "story" from agronomic scientists, although still unfolding as new research is published, is that higher nutrient use efficiency has already been achieved within the context of cereal yield increases over the past 30 years or more. Furthermore, the future prospects for simultaneous gains in both nutrient efficiency and cereal crop yields are also strong as long as the appropriate technology investments continue. The pertinent technology advances that are essential to achieve the latter goal are outlined in this synopsis.

Defining Nutrient Use Efficiency (NUE)

In any discussion of this topic (whether among peers or between agronomic scientists and the broader society), definitions are very important. Depending on the calculation used, it is entirely possible that there are different outcomes in NUE for any given combination of a fertilizer input rate and cereal crop yield (whether grain alone, or when whole-plant yield is considered). Here we will focus on nitrogen as an example nutrient, in part because it (along with phosphorus) has the most negative environmental consequences when losses occur. In this brief overview, I will assume that we are discussing the relative NUE (based on the delta gain, relative to an untreated control, in cereal yield per unit of nitrogen fertilizer applied). In addition, agronomic sciences are now increasingly measuring nitrogen internal efficiency (NIE) in these systems evaluations because NIE is a useful metric to evaluate cereal kernel yields relative to whole-plant nitrogen uptake. Numerous other efficiency metrics are available (including, for example, nitrogen recovery efficiency-NRE-which measures the gain in crop nitrogen uptake per unit of nitrogen fertilizer added, as well as nitrogen conversion efficiency-NCE-which measures plant biomass yield per unit nitrogen content at any growth stage).

Genetic Improvements in NUE

Frequently, the uninformed public opinion is that higher cereal yields can only be realized with ever higher nutrient application rates. A common misperception is that cereals like maize, wheat and rice are becoming ever more reliant on nutrient inputs like nitrogen, and that higher nutrient application rates are required. However, numerous studies have shown that yield gains in cereal crops over the past 50 years have generally been accompanied by improvements in NUE. Thus, for example, nitrogen fertilizer rates per unit area have been little changed for the last 35 years of maize production in the United States despite almost a doubling of grain yield in that time. Recent review papers have confirmed that modern maize hybrids achieve higher NIE because of factors like more later-season nitrogen uptake, improved nitrogen conversion efficiencies, better abiotic stress tolerance, and-sometimes-higher grain harvest index. Maize breeding companies around the world are now focused on continuing to improve NUE as a targeted trait (instead of just happening to result as a byproduct of breeding for higher grain yield). Even among current hybrids, there are substantial often differences in NUE. Thus far, there no commercially-available transgenic traits for improved NIE or NUE in any cereal crop, but such developments may help speed future progress towards nutrient and associated environmental efficiencies.

As plant trait phenotyping approaches become better known and cheaper to implement in large-scale cereal breeding programs, there are strong prospects for continued genetic improvements in NIE and overall NUE with tomorrow's higher yielding cultivars. Even if agronomic optimum nitrogen rates don't actually decline on a per-unit-area basis, the prospects are encouraging for continuing to achieve gains in N fertilizer rates required per unit of cereal grain yield.

Fertilizer Technology Improvements to NUE

Technology changes over the last 30 years in fertilizer source, placement and timing are all contributing to NUE gains in cereal production systems around the world. Fertilizer technology gains are sometimes leading to real reductions in N rates per unit area in cereal production fields that are now achieving much higher yields. From the nitrogen source perspective, enhanced efficiency fertilizers (such as nitrification inhibitors) that are now commercially available for both dry and liquid nitrogen fertilizer products are leading to new opportunities to better time mineral N availability with the periods of highest plant nitrogen uptake. Enhanced efficiency nitrogen fertilizers are also directly beneficial in reducing nitrogen losses to the atmosphere (as nitrous oxides) or to water sources (as nitrate). Placement technologies in both rain-fed and irrigated production systems have also advanced to allow later-season nitrogen applications with little crop loss risk. New injection placement systems are also permitting more uniform application at the desired soil depth for improved nutrient availability to crop roots. Variable-rate nutrient applications with precision GPS guidance offer even more prospects for improving NUE in soils with varying texture and organic matter. Some of the biggest fertilizer management gains in NUE can now occur with better timing of N applications. Whereas previously single-time nitrogen applications (sometimes well in advance of crop seeding) were the dominant system for cereal producers, more and more NUE gains are now practically possible with split nitrogen application systems.

As both the genetic technologies and the fertilizer technologies evolve, agronomic research must devote more energy to integrating these technologies to achieve both optimum yields and lowest possible losses per unit of nitrogen applied. Fertilizer source, rate, timing and placement research in cereal crops from over 30 years ago has limited relevance to modern cultivars and modern fertilizer technologies. Ideally, new nutrient management research should focus on both productivity and environmental efficiencies simultaneously.

Crop Management Improvements to NUE

The identification of optimum nutrient application systems for higher cereal yields can never be isolated from the rest of the crop production system. The same is true for identification of nutrient management systems that best limit nutrient losses to the environment. Some of the principal crop management changes that can affect NUE and NIE parameters for given cultivars are tillage practices, crop rotation, water management (drainage, irrigation and artificial barriers like plastic film), seeding date, plant density, pest management, and post-harvest residue management or manure/amendment applications. Unfortunately, too much of the nutrient management literature is dominated by nutrient treatment comparisons for a single cultivar grown with a single crop management package. While nutrient management research for a given region always needs to seek to be relevant to current production practices, agronomic scientists should (where financially possible) be devoting additional resources to optimum nutrient management for "next-generation" crop production systems, including that of expanded use of variable rate nutrient applications.

By way of an example, although most maize production in the U. S. Corn Belt today still relies on full-width conventional tillage with broadcast macro-nutrient applications, my current research group's emphasis at Purdue University seeks to determine optimum nitrogen, phosphorus and potassium management (source, rate, placement, and/or timing) in strip-till maize production because I anticipate a continued shift to that system for both input cost and environmental concern reasons. Our group is also pursuing nutrient balance issues (e. g. N : P or N : K) in maize production systems because of the potential importance to final grain yield associated with maintaining a critical balance in different plant components during the crop's life cycle.

Another successful example of a crop systems approach to nutrient management is that of the Global Maize research effort supported by IPNI. In that coordinated research approach, researchers around the world are comparing nitrogen management treatments within the crop management context of current "Farmer Practice" versus "Ecological Intensification". The latter may involve superior-yielding maize hybrids, higher plant densities, additional pest management, and/or alternate post-harvest residue management in addition to the comparison of nitrogen rates or nitrogen sources. Those studies all involve measurement of whole-plant nutrient uptake and soil nutrient properties to answer the relevant NUE questions. Some of those studies also involve measurement of nutrient losses to air and water.

Conclusions

Agronomic science generally has a "good news story" to tell others about past gains in NUE as cereal yields increased (as long as excessive nutrient applications per unit of yield were avoided). The "good news story" is less well documented on the environmental losses of nutrients applied, and especially so with cereal production systems combining the best technologies available in genotype, fertility practices, and ecologically-intensive crop management. However, there are numerous examples of lower nutrient losses to the environment as individual nitrogen conserving technologies were adopted.

Advancing technologies on the genetic, fertilizer and crop management frontiers offer considerable hope for achieving higher NUE in cereal production systems as yields increase. The past genetic gains in NIE (at least for maize) have been particularly impressive, as have the improvements in nutrient source and precision application technologies to achieve enhanced nutrient recovery by cereal crop plants where and when these nutrients are needed most.

However, significant challenges remain in achieving and documenting simultaneous NUE improvements and environmental mitigation in cereal production. These challenges are best addressed in better-coordinated and systems-relevant research that is adequately funded by industry as well as by the national and local governments (i. e. the societies that need both higher cereal crop yields and lower nutrient losses to the atmosphere). In addition, the soil fertility or plant nutrition scientists involved in that research should expand partnerships with plant breeders, crop physiologists, environmental ecologists, agricultural engineers and (or) cropping systems specialists from public and private institutions where possible. Such interdisciplinary research (and dialogue with public) is both more readily achievable and more essential today to achieve tomorrow's more sustainable food security.

小麦玉米轮作制度下养分专家系统的推荐施肥应用*

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摘　要：本研究旨在探索小麦/玉米轮作体系中养分专家系统定位持续应用的效果。2011—2013 年采用田间试验的方法定位研究了两个试点养分专家系统推荐施肥（农民自己应用系统）连续四季作物的效果。两个试点两年四季连续定位应用养分专家系统的肥料推荐（OPTe）的作物产量和吸氮量与测土推荐（OPTs）、农民习惯施肥（FP）分别比较，均没有明显的差异。在保证高产的条件下，OPTe 处理小麦玉米轮作的施氮量较 FP 处理节约 33%~48% 氮肥，氮肥利用率均明显提高了 10 ~ 13 个百分点。养分专家系统的肥料推荐能保持作物持续高产，稳定性较好，是值得进一步推广应用的新的肥料推荐工具。

关键词：养分专家系统；小麦—玉米轮作；产量；氮肥利用效率

Fertilizer Recommendation Based on Nutrient Expert System under Winter Wheat and Summer Maize Rotation*

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Abstract: The purpose of this study was to explore the successive effect of fertilizer recommendation based on Nutrient Expert system under wheat and maize rotation. Two field experiments were conducted by farmers themselves in Xiangfen site and Yaodu site in 2011 - 2013. Results indicated that yields and N uptake of four successive crops from the treatment of OPTe (fertilizer recommendation based on Nutrient Expert) were not significant, compared with the treatment of OPTs (fertilizer recommendation from local department based on soil test) and FP (farmer practice), respectively. Compared with farmer practice, the amount of nitrogen fertilizer in the OPTe treatment was saved by 33-48% and the nitrogen use efficiency increased by 10-13 percentage points under the condition of higher yield. Fertilizer recommendation based on Nutrient Expert could help to produce sustainable and stable yield. Therefore, Nutrient Expert is a new tool of fertilizer recommendation and worthy to be popularized.

Key words: Nutrient expert; Wheat and maize rotation; Yield; Nitrogen use efficiency

小麦和玉米都是我国重要的粮食作物，2013 年我国小麦、玉米的播种面积分别占粮食作物播种面积的 21.5% 和 22.1%，两种作物的总产量分别占粮食总产的 20.3% 和 36.3%[1]。在土壤—作物生产系统中，施肥能调节营养物质在作物体内和土壤中的状况，改善作物生长发育的内在和外界环境，最终达到提高产量、改善品质、培肥地力，持续发展的目的。因此，肥料发挥着不可替代的物质支撑作用[2]。施用化肥在过去、现在和将来都是我国最有效的农产品增产措施之一[3]。随着人口的不断增加，国家对粮食的需求也不断增长，农民通过增加肥料投入来提高粮食产量，形成了我国特有的靠化肥的大量投入来增加单产的农田高强度利用生产体系[2]。

* 基金项目：国际植物营养研究所项目（IPNI - Shanxi - 2013）
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2013 年我国种植业化肥施用量已高达 5 498 万吨（折纯量），占世界化肥消费量的 1/3 以上，其中，粮食作物的化肥总用量为 2 782 万吨，占种植业化肥总用量的 50.6%[4]。但肥料的不合理施用或过量施肥现象在各地农业生产中普遍存在，据巨晓棠和谷保静调查，过量施氮田块约占总调查田块的 33%[5]，导致氮肥平均利用率仅为 30%~41%[6]，较发达国家低 10 ~ 20 个百分点。这样，一方面表现为投入增加、生产效益低下，造成资源浪费；另一方面对环境产生负面效应，影响农业的可持续发展。因此，用好肥料资源、提高肥料利用效率是关系到国家粮食安全和环境质量的重大科技问题[2]。

推荐施肥就是要解决需要什么肥，各需多少，在什么时期施，怎么施肥等一系列问题[7-8]。国内外的专家、学者在农作物推荐施肥的研究和实践中，发展了各种施肥推荐的方法和模型，如地力分区（级）配方法、养分平衡法、地力差减法、肥料效应函数法、养分丰缺指标法、氮磷钾比例法、土壤养分系统研究法[9-16]，耕层氮素实时监控技术、区域平均施氮量、实地养分管理 SSNM（Site-Specific Nutrient Management）[17-19]、4R 技术[20]（正确的品种 right source，正确的用量 right rate，正确的时间 right time，正确的位置 right place），等等，在农业生产中均得到了一定程度的研究和应用，从田间尺度发展到区域尺度，取得了较大的进展和成就。值得提出的是，各种施肥模型均有优点和技术特点，也都存在不足。由于受技术、资金、人力、时效性等因素的影响，上述方法在我国人多地少、土壤基础肥力差、养分空间变异大、分散经营、地块面积小、复种指数大、倒茬时间紧的农业生产体系中应用均有其特殊的难度，而生产实践中迫切需要简单、实用、便于操作的施肥推荐系统。养分专家系统（Nutrient Expert）是基于作物产量反应和农学效率的推荐施肥的一种新方法，近几年由国际植物营养研究所（IPNI）开发成功。它是以改进的 SSNM 和改进的 QUEFTS（Quantitative Evaluation of the Fertility of Tropical Soils）模型参数为指导的养分管理和推荐施肥为原则，同时考虑大、中微量元素的全面平衡，并应用计算机软件技术把复杂和综合的养分管理原则智能化形成的，可以为不同用户（当地技术推广人员、种植大户、家庭农场、专业种植合作社）掌握的推荐施肥专家系统，并在河北、河南、山东、山西及东北三省等地的当季作物（小麦或玉米）得到了初步应用，并在稳产条件下取得了节肥增效的良好效果[14,21-24]。而在小麦—玉米轮作体系条件下，应用养分专家系统连续定位推荐的效果如何，是一个值得研究的课题。本研究于 2012—2013 年应用该系统在临汾市尧都区和襄汾县开展了两年四季的定位研究，以期为养分专家系统更广泛的推广应用提供理论依据。

1 材料与方法

临汾市是山西南部地区重要的冬小麦/夏玉米轮作主产区，属半干旱温带大陆性气候，多年平均气温在 12.6℃左右，年均降水量 498 mm，无霜期 195 d 左右。试验期间 2011 年、2012 年、2013 年三年试验期间平均气温分别为 13.3℃、13.7℃、14.5℃，年降水量分别为 630.8 mm、497.5 mm、533.1 mm，但降水量分布不均匀，主要集中在 7—9 月，值得指出的是 2013 年 3—4 月持续低温，较往年同期低 2℃左右，5 月下旬至 6 月上旬又遭遇寡照降雨，造成小麦一定程度的减产。试验选在临汾市襄汾县西贾乡义顺村和尧都区乔李镇南麻村进行，试验前采集耕层 0 ~ 20 cm 土壤按常规方法测定[25]，土壤的理化性状列于表 1，土壤类型为石灰性褐土，质地为中壤。试验设 7 个处理，包括 OPTe、OPTe-N、OPTe-P、OPTe-K、CK、OPTs 和 FP，随机排列，3 ~ 4 次重复，小区面积 33.5 m^2。其中，OPTe 是通过与农户交流后，帮助农民根据自己的施肥情况、作物产量等信息输入养分专家模型软件运行获得，OPTe-N、OPTe-P、OPTe-K 是指在 OPTe 基础上不施氮肥、不施磷肥和不施钾肥，CK 为不施任何肥料，OPTs 为基于土壤测试结果，由当地农业部门给出的肥料推荐，FP 为农民习惯施肥（一般是复合肥和尿素一次性基肥施入），具体的施肥方案列于表 2。试验所用

肥料为尿素（46% N）、过磷酸钙（12% P_2O_5）和氯化钾（60% K_2O）。小麦季磷钾肥和 45% 的氮肥于播前撒施作基肥施用，55% 的氮肥于翌年 3 月下旬撒施结合灌溉施用。玉米季磷钾肥和 40% 的氮肥在夏玉米 5～6 叶期结合中耕以条施方式施用，玉米追肥在玉米 10 叶期穴施覆土后灌溉一次施入。冬小麦生长期间，浇入冬水、返青水和抽穗水各一次，玉米生长期间，浇水 2 次，锄草、治虫等管理按当地习惯，有关试验播种收获信息列于表 3。试验收获时采集各处理植株样和土壤样品，用常规方法[25]分析植株全氮、全磷、全钾和土壤硝态氮。数据处理采用 Excel 和 SPSS 10.0 软件进行了统计分析。有关氮肥农学效率、氮肥利用率计算公式：

氮农学效率（AEN，kg/kg）＝（施氮区产量－不施氮区产量）/施氮量

氮肥利用率（NUE,%）＝（施氮区吸氮量－不施氮区吸氮量）/施氮量 ×100

表 1　供试土壤的理化性质

Table 1　The physical and chemical properties of the tested soil

地点 Location	pH	硝态氮 NO_3-N（mg/kg）	有机质 OM（g/kg）	有效磷 Avail. P（mg/kg）	速效钾 Avail. K（mg/kg）
襄汾 Xiangfen	8.32	28.84	21.22	18.47	119.6
尧都 Yaodu	8.41	35.55	13.53	36.12	213.4

表 2　2011—2013 小麦/玉米施肥方案

Table 2　Treatment design for wheat and maize in 2011－2013

处理 Treatment	小麦季养分施用量（kg/hm²）Fertilizer application in wheat			玉米季养分施用量（kg/hm²）Fertilizer application in maize		
	N	P_2O_5	K_2O	N	P_2O_5	K_2O
襄汾 Xiangfen						
OPTe	182	92	71	111	62	60
OPTe-N	0	92	71	111	62	60
OPTe-P	182	0	71	111	62	60
OPTe-K	182	92	0	111	62	60
CK	0	0	0	0	0	0
OPTs	210	90	75	210	45	45
FP	292	30	30	271	165	0
尧都 Yaodu						
OPTe	182	103	83	182	62	60
OPTe-N	182	103	83	0	62	60
OPTe-P	182	103	83	182	0	60
OPTe-K	182	103	83	182	62	0
CK	0	0	0	0	0	0
OPTs	210	90	75	200	75	75
FP	271	165	0	276	72	0

注：襄汾小麦季目标产量设计为 8.5 t/hm²，氮、磷、钾反应分别为 2.5 t/hm²、1.0 t/hm² 和 0.75 t/hm²；玉米季目标产量为 9.0 t/hm²，氮、磷、钾反应分别为 1.0 t/hm²、0.5 t/hm² 和 0.5 t/hm²。尧都小麦季目标产量设计为 9.0 t/hm²，氮、磷、钾反应分别为 2.5 t/hm²、1.25 t/hm² 和 1.0 t/hm²；玉米季目标产量为 9.0 t/hm²，氮、磷、钾反应分别为 2.0 t/hm²、0.5 t/hm² 和 0.5 t/hm²

Note: The target yield for wheat in Xiangfen was 8.5 t/hm², and the yield responses for N, P and K were 2.5 t/hm², 1.0 t/hm² and 0.75 t/hm², respectively. The target yield for maize in Xiangfen was 9.0 t/hm², and the yield responses for N, P and K were 1.0 t/hm², 0.5 t/hm² and 0.5 t/hm², respectively. The target yield for wheat in Yaodu was 9.0 t/hm², and the yield responses for N, P and K were 2.5 t/hm², 1.25 t/hm² and 1.0 t/hm², respectively. The target yield for maize in Yaodu was 9.0 t/hm², and the yield responses for N, P and K were 2.0 t/hm², 0.5 t/hm² and 0.5 t/hm², respectively