小麦养分专家系统用户使用手册

User manual for Nutrient Expert® for wheat

小麦养分专家系统（中国版本）是基于计算机的决策支持系统，能够帮助科研人员或技术推广人员迅速给出小麦的施肥决策。该系统仅需要用户提供地块基本信息，通过回答一系列简单问题，用户就可以得到基于地块信息的施肥指导。该系统可以在没有土壤测试条件下使用，具有广泛的应用前景。

INTERNATIONAL PLANT NUTRITION INSTITUTE

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INTERNATIONAL PLANT NUTRITION INSTITUTE

小麦养分专家系统是基于计算机的决策支持系统，可以帮助当地科研人员 / 农业技术推广人员针对小麦的生长环境快速做出施肥决策。小麦养分专家系统通过确定当地的目标产量以及为达到这个目标产量提供合理的施肥管理措施，从而能够帮助农民提高产量和经济效益。该软件仅需要农民或当地的科研人员提供一些简单的信息。通过回答一系列简单的问题，用户就可以得到基于特定地块条件以及当地可利用的肥料资源的施肥指导。该系统还可以通过比较农民习惯施肥和推荐施肥措施的成本和收益，提供简单的经济效益分析。另外，小麦养分专家系统提供了快捷帮助、即时的图表概要，加上软件中一些模块增加了导航的适用性，使该软件在设计上成为一种易学的工具。

小麦养分专家系统提供的施肥指导原则基于 以下目标：

○ 充分利用土壤基础养分供应
○ 提供充足的 N、P 和 K 及其它肥料养分，使养分胁迫降到最低并获得高产
○ 在短、中期内获得高的效益
○ 避免作物养分的奢侈吸收
○ 保持土壤肥力

小麦养分专家系统可以帮助您：

- 评估农户当前养分管理措施
- 基于可获得产量确定一个有意义的目标产量
- 给出选定目标产量下的 N、P 和 K 施肥量
- 将 N、P 和 K 施肥量转换为肥料实物量
- 确定合适的施肥措施（合适的用量，合适的肥料种类、合适的位置，合适的施用时间）
- 比较当前农民和推荐施肥两种措施下预期的经济效益。

假设与条件：

小麦养分专家系统的指导原则是基于以下条件提出来的：

○ 整个生育期没有严重的水分限制（如干旱等）
○ 酸性和（或）微量元素的任何问题均得到妥善处理
○ 使用的是当地适宜的小麦品种
○ 生育期没有严重的病虫害
○ 肥料施在了正确的位置

疑问与软件更新

想了解该软件更多信息请联系国际植物营养研究所中国项目部，010-82106205, Email：phe@ipni.net

关于该软件的最新版本以及更新，请访问 http://china-zh.ipni.net

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一、4 大基本模块

每个模块至少包含两个问题，用户在一系列供选答案中选择和（或）在设计的文本框中输入数值就可以回答这些问题。每个模块都提供可被打印或保存的文档（PDF）。用户可以在不同模块间进行切换和修改，但用户必须认识到在某个模块中的修改会影响到其它模块（模块间数据是共享的）。

当前农民养分管理措施及产量

该模块提供了当前农民养分管理措施及可获得产量的总体概况。该模块的输出报告是一个包括肥料施用时间、肥料施用量以及肥料 N、P_2O_5 和 K_2O 用量的概要性表格。

养分优化管理施肥量

该模块在预估的产量反应和基于 SSNM 养分管理原则基础上，推荐出一定目标产量下的 N、P 和 K 肥料需要量；也可通过已有信息对某个新地区可获得产量和产量反应进行预估进而推荐施肥。其它影响养分供应的因素或措施——如有机肥的投入（粪便）、作物残茬管理、上季作物管理等——都需要考虑，从而调整 N、P 和 K 肥料的施用量。

肥料种类及分次施用

该模块帮助用户将推荐的 N、P 和 K 养分用量转换为当地已有的单质或复合肥料用量，并符合 SSNM 优化施肥原则。该模块的输出报告是一个针对特定生长环境的最佳养分指导原则，即包括选择合适的肥料种类、确定合适的施肥量以及合适的施肥时间。

效益分析

该模块比较了当前农民施肥措施及推荐施肥措施两种方式下预估经济效益或实际经济效益。它展示了一定目标产量下推荐施肥管理措施带来的预期收益变化。经济效益分

析需要用户定义农产品和种子价格，肥料投入成本是根据“设置”页面中用户所定义的试验地点的肥料价格来计算。输出报告显示了一个简单的利润分析，包括收入，化肥和种子成本，预期效益以及采用优化施肥带来的效益的变化。

设置页面

设置页可以作为用户对当地具体信息的自定义数据库，如：田块面积单位及产量（地点描述）、当地已有的肥料种类、养分含量及价格（无机肥料、有机肥料）。输入的数据或信息都会在关闭页面后自动保存。

使用和操作软件步骤

(1) 打开 NE Wheat.mde 来启动该软件。

(2) 在【主页】，点击【设置】（在主页的右上方）。

a. 点击【地点描述】、【无机肥料】和【有机肥料】，查看或补充地点信息以及肥料品种、养分含量和价格信息。

b. 点击【关闭】返回【主页】。输入或选择的数据将会保存以备五个模块调用。现在就可以准备运行不同的模块了。

(3) 在【主页】，点击代表 4 个模块的 4 个按钮中的任何一个。在所选模块（如当前农民养分管理措施），依次回答屏幕上连续显示每一个问题。

(4) 点击页面右下角的【下一步】进入下一个模块。也可以通过点击模块标签切换到其它任意模块（如养分优化管理施肥量）。

注意：问题后面的 ? 按钮可以链接到对该问题的解释或简短的背景介绍。

(5) 你可以在任何时间通过点击【返回】或模块标签切换返回到前一个模块。

(6) 如果要打印某个模块的报告或输出结果，可以点击页面左下角的【报告】按钮。

(7) 点击【重置】按钮将会清除当前模块所有已输入的数据或回答的问题，点击【关闭】按钮会关闭当前模块并返回到【主页】。一旦返回【主页】或切换到其它模块，该模块所有已输入数据会自动保存。

(8) 要关闭并退出软件，点击【主页】和【退出】即可。

二、设置界面

输入信息：

- 当地面积单位和产量单位，标准单位为“公顷”和“公斤”，也可以在设置中编辑改用当地所用的计量单位，如“亩”
- 标明有效 N、P_2O_5 和 K_2O 养分含量的当地化肥种类以及每公斤化肥的价格
- 标明有效 N、P_2O_5 和 K_2O 养分含量的当地有机肥或有机物料种类以及每公斤有机肥的价格

输出信息：这些信息用于软件不同的模块和函数调用

小麦养分专家系统能够储存或保存当地具体信息，如当地计量单位、可用肥料种类以及价格。当首次使用或在新的区域使用该软件时，用户首先需要进入“设置”窗口进行设置。再次使用已知地点信息，用户仅需要选择地点和编辑已有的信息。

1. 地点描述

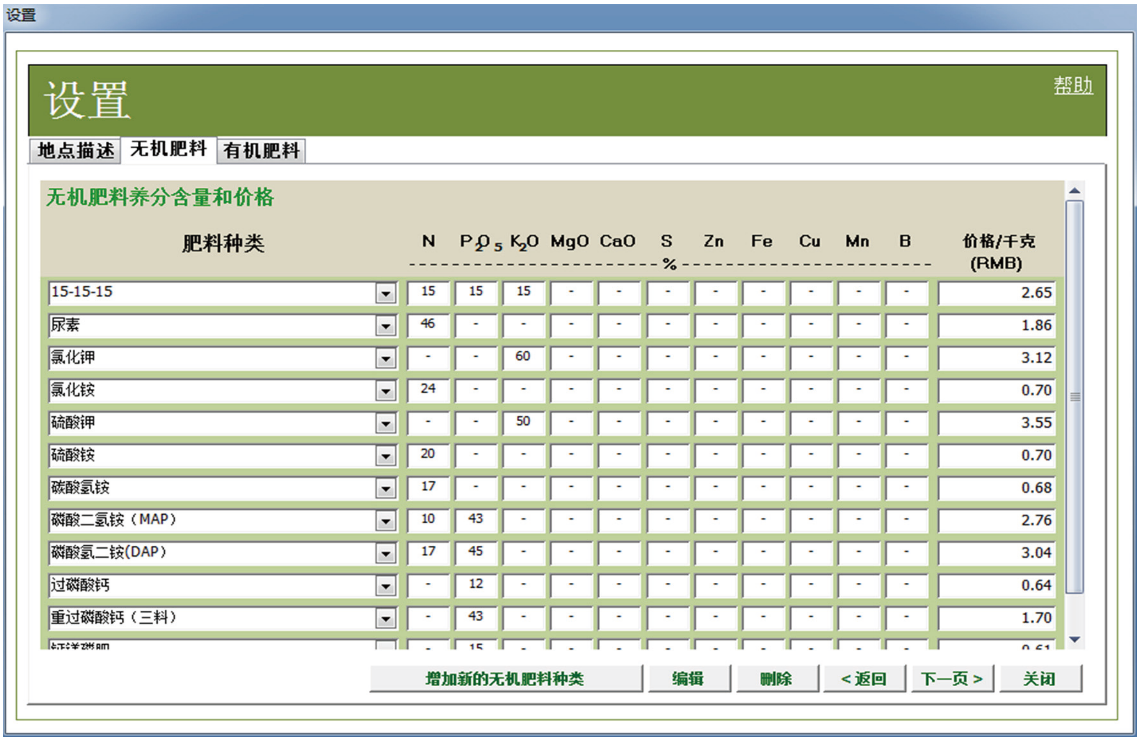
用户可以选择区域、省份和生长季节，选择或添加一个地名。当地面积单位、籽粒产量单位与标准单位的转换（如公顷、公斤）已经在本页输入，当需要时，可以在软件的其它模块调用。

如果输入了几个位置信息，要确认一定在地点信息旁边激活（使已输入地点信息处于“打钩”状态）以确保输入的地点信息处于“激活”状态。

2. 化肥

用户可以通过选择已有的肥料清单或 / 和添加新的肥料种类，确认化肥信息齐全。其中，化肥信息包括：肥料养分含量（%N、% P_2O_5 和 %K_2O）以及每公斤的肥料价格。

注意：对于每一个地点，肥料的种类、养分含量以及价格信息必须齐全。点击“编辑”按钮可编辑、修改和输入肥料信息，输入“数值”后，点击“保存”按钮。



肥料种类	N	P_2O_5	K_2O	MgO	CaO	S	Zn	Fe	Cu	Mn	B	价格/千克 (RMB)
	%											
15-15-15	15	15	15	-	-	-	-	-	-	-	-	2.65
尿素	46	-	-	-	-	-	-	-	-	-	-	1.86
氯化钾	-	-	60	-	-	-	-	-	-	-	-	3.12
氯化铵	24	-	-	-	-	-	-	-	-	-	-	0.70
硫酸钾	-	-	50	-	-	-	-	-	-	-	-	3.55
硫酸铵	20	-	-	-	-	-	-	-	-	-	-	0.70
碳酸氢铵	17	-	-	-	-	-	-	-	-	-	-	0.68
磷酸二氢铵（MAP）	10	43	-	-	-	-	-	-	-	-	-	2.76
磷酸氢二铵(DAP)	17	45	-	-	-	-	-	-	-	-	-	3.04
过磷酸钙	-	12	-	-	-	-	-	-	-	-	-	0.64
重过磷酸钙（三料）	-	43	-	-	-	-	-	-	-	-	-	1.70

3. 有机肥

用户可以通过选择已有的有机肥清单或 / 和添加新的有机肥种类，确认有机肥料信息齐全。有机肥信息包括：养分含量（%N、% P_2O_5 和 %K_2O）以及有机肥料的价格。

肥料种类	N	P_2O_5	K_2O	MgO	CaO	S	Zn	Fe	Cu	Mn	B	价格/千克 (RMB)
	%											
一般堆肥	0.333	0.234	1.135	-	-	-	-	-	-	-	-	0.00
人粪尿	9.973	3.254	3.366	-	-	-	-	-	-	-	-	0.00
农家肥	1.262	0.618	1.606	-	-	-	-	-	-	-	-	0.00
厩肥	1.070	0.735	1.401	-	-	-	-	-	-	-	-	0.00
小麦秸秆堆肥	0.940	0.424	1.277	-	-	-	-	-	-	-	-	0.00
水稻茎秆堆肥	1.405	0.577	1.689	-	-	-	-	-	-	-	-	0.00
沤肥浸渍液	0.635	0.573	1.766	-	-	-	-	-	-	-	-	0.00
牛粪	1.299	0.744	2.192	-	-	-	-	-	-	-	-	0.00
牛粪尿	2.462	1.289	3.479	-	-	-	-	-	-	-	-	0.32
猪栏粪	0.929	1.014	1.144	-	-	-	-	-	-	-	-	0.00
猪粪	3.773	2.508	3.005	-	-	-	-	-	-	-	-	0.32

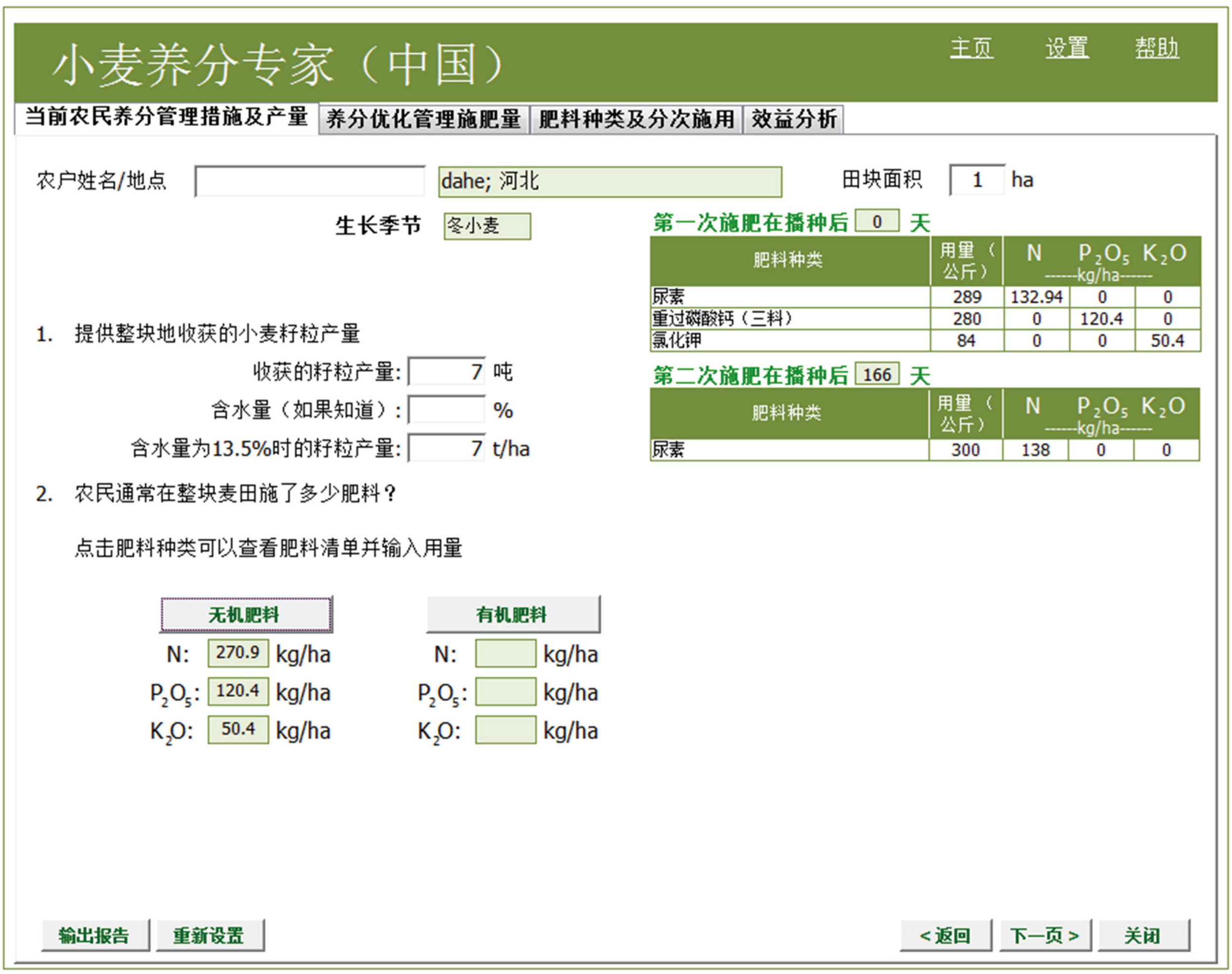
三、当前农民养分管理措施

输入信息：

- 当前农民典型气候条件下该季作物的产量
- 当前农民养分管理措施—肥料用量（无机肥料、有机肥料）、施肥时间

输出信息：

- 当前农民养分管理措施的概要表格（每次 N、P_2O_5 和 K_2O 的施用量）
- 无机肥料和有机肥料 N、P_2O_5 和 K_2O 的总施用量



当前农民养分管理措施及产量是指农民在作物生长季节肥料投入情况。它包括小麦不同生长阶段施用的肥料种类及用量。用户需要提供肥料的施用量（以 kg 表示）以及施用时间或以播种后天数表示（DAP）。该模块的输出是包含了每次施用的肥料种类和 N、P_2O_5 和 K_2O 肥料施用量的概要表格（如表 1a），也分别列出了来自无机肥料和有机肥料的 N、P_2O_5 和 K_2O 的施用量（如表 1b）。

小麦养分专家系统需要提供代表性气候条件下过去 3~5 年可获得的产量（不包括飘忽不定的气候条件下异常季节的产量）。如果籽粒含水量未知，则软件将按照 13.5% 的标准含水量将其转化为标准产量数值。

在【效益分析】模块预估效益时需调用当前农民养分管理措施下的产量，同时，当可获得的产量（目标产量）未知时，可以参考农民养分管理下的产量预估可获得产量。当前养分管理措施还可以用于计算肥料投入成本。

表 1a 每次施肥时的无机肥料施用量

第一次施肥在播种后 0 天

肥料种类	用量（公斤）	N	P_2O_5	K_2O
		------kg/ha------		
尿素	289	132.94	0	0
重过磷酸钙（三料）	280	0	120.4	0
氯化钾	84	0	0	50.4

第二次施肥在播种后 166 天

肥料种类	用量（公斤）	N	P_2O_5	K_2O
		------kg/ha------		
尿素	300	138	0	0

表 1b 小麦季总的无机和有机肥料施用量

	无机肥料		有机肥料	
N:	270.9	kg/ha		kg/ha
P_2O_5:	120.4	kg/ha		kg/ha
K_2O:	50.4	kg/ha		kg/ha

四、养分优化管理施肥量

输入信息：

○ 可获得产量：如果知道可以直接填入数值；否则可以通过一些可选项进行估算，包括作物生长环境描述（如灌溉或雨养，旱涝发生频率，除氮磷钾外的其他土壤障碍因子）。如果土壤中已知某种或几种中微量元素缺乏，在输出菜单中会根据选定的中微量元素进行施肥推荐。

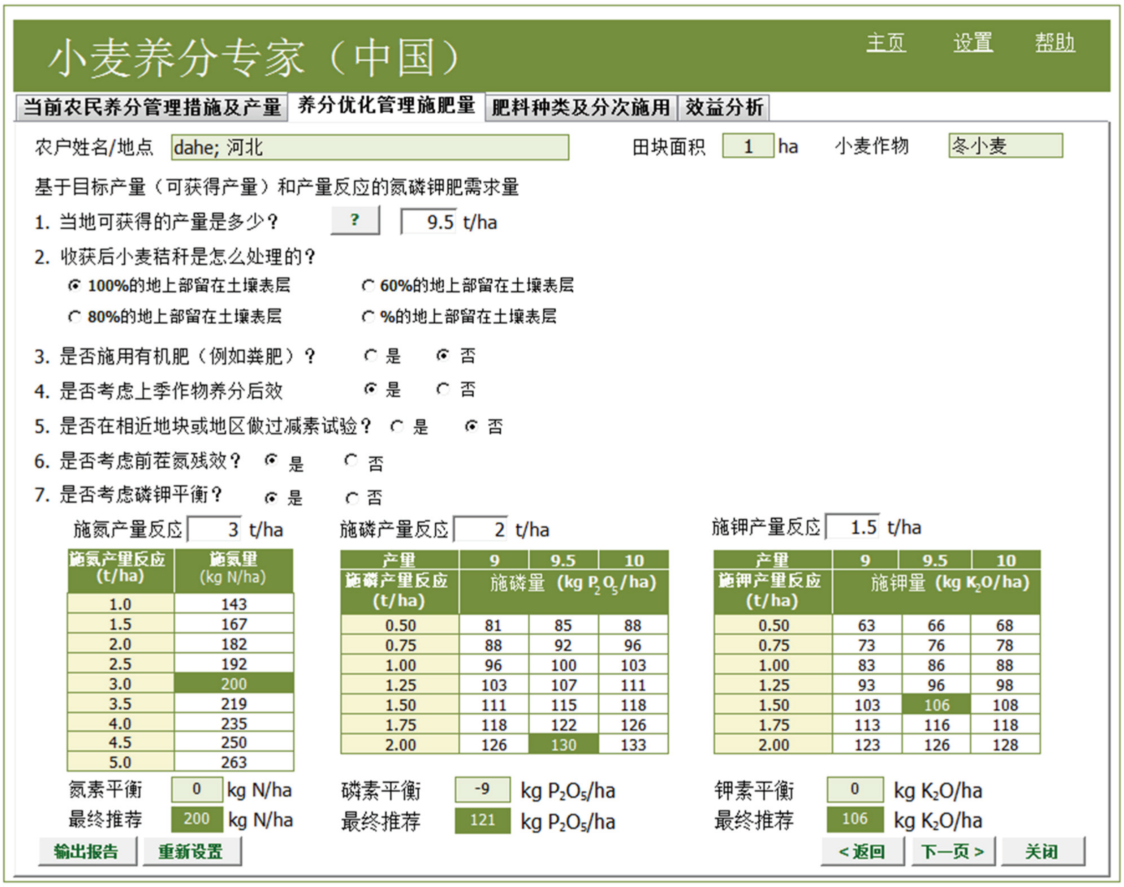
○ 作物秸秆处理方式，有机肥施用和上季作物养分带入情况

○ 作物对氮磷钾肥的产量反应：如果知道可以直接填入数值；否则可以通过一些可选项进行估算，包括土壤肥力指标如土壤质地和颜色，有机肥施用情况，上季作物信息（产量，施肥量和秸秆还田情况）。

○ 如果有土壤测试结果，则可以根据对应的土壤测试结果（有机质、速效磷和速效钾）的低、中、高等级，进行产量反应估算，进而给出推荐施肥量。

输出信息：

- 根据可获得目标产量和产量反应给出的氮磷钾推荐施肥量
- 养分平衡或必要的调整



1．确定养分优化管理 N、P 和 K 施肥量

养分优化管理施肥量模块根据目标产量和产量反应确定 N、P_2O_5 和 K_2O 用量，符合实地养分管理原则。在小麦养分专家系统中，氮肥用量（FN）根据产量反应（目标产量与不施氮小区的产量差）和氮肥的农学效率（AEN）确定（表 1）。磷肥用量（FP）根据磷肥产量反应（如 1 吨产量反应需 30 kg P_2O_5）和维持土壤磷素平衡两部分组成，维持土壤磷素平衡部分相当于需要归还一定目标产量下作物地上部 P 养分移走量；同样，钾肥用量（FK）根据钾肥产量反应（如 1 吨产量反应需 40 kg K_2O）和维持土壤钾素平衡两部分组成，维持土壤钾素平衡部分相当于需要归还一定目标产量下作物地上部 K 养分移走量，具体比例取决于作物残茬还田比例。

表 1 基于氮肥产量反应和氮素农学效率的小麦氮肥推荐量

氮素产量反应 (t/ha)	推荐施氮量 FN (kg/ha)	氮素农学效率 AEN
0.25	42	6.0
0.50	71	7.0
0.75	94	8.0
1.00	118	8.5
1.25	132	9.5
1.50	143	10.5
1.75	159	11.0
2.00	167	12.0
2.25	173	13.0
2.50	185	13.5
2.75	196	14.0
3.00	200	15.0
3.25	210	15.5
3.50	219	16.0
3.75	227	16.5
4.00	235	17.0
4.25	243	17.5
4.50	250	18.0
4.75	257	18.5
5.00	263	19.0

目标产量是特定生长季节采用最佳养分管理措施能够获得的产量。可获得产量和产量反应可结合缺素小区确定。可获得产量是田间最佳管理措施且没有任何养分限制条件下的平均产量。

在缺素小区试验资料缺乏时，如未做过缺素试验新的小麦产区，小麦养分专家系统可根据作物生长条件（如气候）和土壤肥力状况对可获得产量和 N、P 和 K 肥的产量反应进行估算。该软件将通过预估 N、P 和 K 肥的产量反应对未做过减素试验的新的小麦产区进行养分推荐，这种情况下需要进行田间验证。

在“预估可获得产量”和“预估产量反应”部分，在回答一系列问题后点击“预估”按钮可得到相应参数。

2．可获得产量和目标产量的范围

本软件中设定的可获得产量范围为 4-9.5 t/ha，可获得产量也可以由用户确定或进行预估。

○ 如果可获得产量已知，用户可以在第一个问题的文本框中直接输入。用户自定义的可获得产量的范围应该在 4 t/ha 与当地当季小麦最大可获得产量两者数值之间。

○ 如果用户或农民对当地当季小麦最佳可获得产量没有把握，用户可以通过点击问题 1 后面的 [?] 按钮链接到“预估可获得产量”窗口。

3. N、P、K 用量表格查询

下面表格给出的是小麦基于目标产量和产量反应的推荐 N、P、K 用量的范例。

N 肥产量反应 : 1.5 t/ha
N 肥用量 : 167 kg N/ha

目标产量 : 6.5 t/ha
P 肥产量反应 : 0.5 t/ha
P 用量 : 63 kg P_2O_5/ha

目标产量 : 6.5 t/ha
K 产量反应 : 0.75 t/ha
K 用量 : 74 kg K_2O/ha

施氮产量反应 (t/ha)	施氮量 (kg N/ha)
1.0	143
1.5	167
2.0	182
2.5	192
3.0	200
3.5	219
4.0	235
4.5	250
5.0	263

氮素平衡 0 kg N/ha
最终推荐 167 kg N/ha

产量	6	6.5	7
施磷产量反应 (t/ha)	施磷量 (kg P_2O_5/ha)		
0.50	59	63	66
0.75	66	70	74
1.00	74	78	81
1.25	81	85	89
1.50	89	93	96
1.75	96	100	104
2.00	104	108	111

磷素平衡 -9 kg P_2O_5/ha
最终推荐 54 kg P_2O_5/ha

产量	6	6.5	7
施钾产量反应 (t/ha)	施钾量 (kg K_2O/ha)		
0.50	49	51	54
0.75	59	61	64
1.00	69	71	74
1.25	79	81	84
1.50	89	91	94
1.75	99	101	104
2.00	109	111	114

钾素平衡 0 kg K_2O/ha
最终推荐 61 kg K_2O/ha

4. 依据有机肥养分施用以及上季作物养分带入的养分计算上季作物养分残效

P 和 K 养分盈亏平衡主要通过考虑作物秸秆处理方式、有机肥施入以及上季作物养分带入量来确定 P 和 K 养分平衡。与小麦总氮需求量相比，有机肥的氮素含量认为可以忽略不计，因此不考虑有机肥的氮素后效。然而，如果上季作物氮肥用量很高（如超过 300 kg N/ha），则需要考虑氮素后效。考虑上季作物养分残效时，最终的施肥量应是不考虑上季养分残效时的施肥量，减去应该考虑的养分残效。为减小减肥的减产风险，在不熟悉地块养分状况和施肥历史的情况下，不建议使用该选项。

五、肥料种类及分次施用

输入信息：

○ 可为当地使用的无机肥料（单质肥料和复合肥料）—已经在设置中确认

输出信息：

○ 将推荐的氮磷钾肥用量转化为可为当地使用的单质或复合肥料用量（当某一复合肥与推荐的养分量不匹配时，建议选择 复合＋单质 选项）

○ 根据作物生长环境提出包括合适的肥料种类、合理的肥料用量和合适的施肥时间的施肥指南。

肥料种类及分次施用模块提供了将推荐的氮磷钾用量转化为可为当地使用的物化的单质肥料或复合肥料用量。需要注意的是，那些复合肥料中，只有能满足优化分次施用指导方法的复合肥料才可以在这里使用。对于不能满足分次施用的复合肥料，建议重新选择“复合肥料 + 单质肥料”选项进行肥料配置。推荐的 N，P_2O_5 和 K_2O 用量会自动从 [**养分优化管理施肥量**] 模块复制过来，用户也可以自己修改这些数值。

这个模块的输出结果是一个针对作物特定生长环境确定的合适肥料种类、合理的肥料用量和合适的施肥时间的施肥指南（图 1）。施肥指南以两种方式表达：1）一是推荐必须在作物关键生育期分次施用的包含肥料种类和肥料用量的汇总表格，2）一页纸的推荐，不仅包括肥料管理指南，还包括其他相关信息（如秸秆还田，有机肥施用），

图 1. 利用当地可供选择的肥料种类推荐的小麦施肥指导范例

并推荐施用石灰（如果土壤 pH<5.3）以及其它中微量元素的施肥指导（如果缺乏）。同时包括一个指示小麦关键生育期的时间表。肥料用量根据地块面积确定，以多少公斤肥料表示。

如何确定作物生育期施肥次数：

取决于农民的喜好和土壤肥力水平，用户可选择两次或三次分次施用氮肥。

关于肥料分次施用的假定

（1）氮肥分次：氮肥依据推荐量的多少在生育期建议施用 2-3 次。

○ 如果 FN ≤ 120 kg N/ha，则建议分两次施用；

○ 如果 FN>120 但 <160 kg N/ha，用户可以选择 2 次或 3 次施肥（如果土壤为壤质或黏质）。如果土壤为砂质，则建议 3 次施用；

○ 如果 FN ≥ 160，建议氮肥分 3 次，分别在基肥、拔节和孕穗期施用。

○ 两次施氮中，基肥比例可以根据土壤氮素养分供应确定或指定基肥比例， 当土壤基础氮素养分供应为低、中和高级别时，分别建议氮肥分次施用比例分别为 60:40、50:50 和 40:60 。用户“指定基肥施用”允许用户输入具体的基肥施用比例，数值在 20-80 之间。

○ 三次施氮中，用户可以选择选择 33:33:33 比例或“指定基肥施用比例”。“指定基肥比例”选项允许用户指定的基肥施用比例数值在 10-60 之间。

○ 氮肥分次施用的注意事项。第一次施肥的实际施用比例可能根据选择的肥料种类（单质或复合肥）不同而较原选定施肥比例略有变化，采用单质肥料较易实现选定施肥比例，而施用复合肥料较难一些。并不是所有情况复合肥都能满足已知的推荐的养分需求，这种情况下可以选择“复合肥＋单质肥”。第一次施肥选用复合肥时，首先以磷肥用量来计算（磷肥用量决定着复合肥的用量），这就意味着氮肥用量可能较原计划用量增加或降低。第二、三次肥料用量（尿素）由第一次施肥量决定。

（2）钾肥分次：

钾肥依据推荐量的多少在生育期间建议施用 1-2 次。

○ 如果土壤为壤质或黏质，并且 FK>60 K_2O/ha，钾肥分两次施用，基追比例则按照 1/2 和 1/2 的比例分两次施用。如果 FK<60 K_2O/ha，则全部钾肥作基肥一次使用。

○ 如果钾肥必须 2 次使用，则 2 次施用的时间与氮肥第一次和第二次的时间相同。

○ 如果钾肥基肥为单质肥料，则第 2 次追肥比例为 50%。

○ 如果钾肥基肥为复合肥，则第一次施钾量随着复合肥中磷肥用量而有些变化，则剩余的钾肥（KCl 或 17-0-17）由第二次施用补齐。

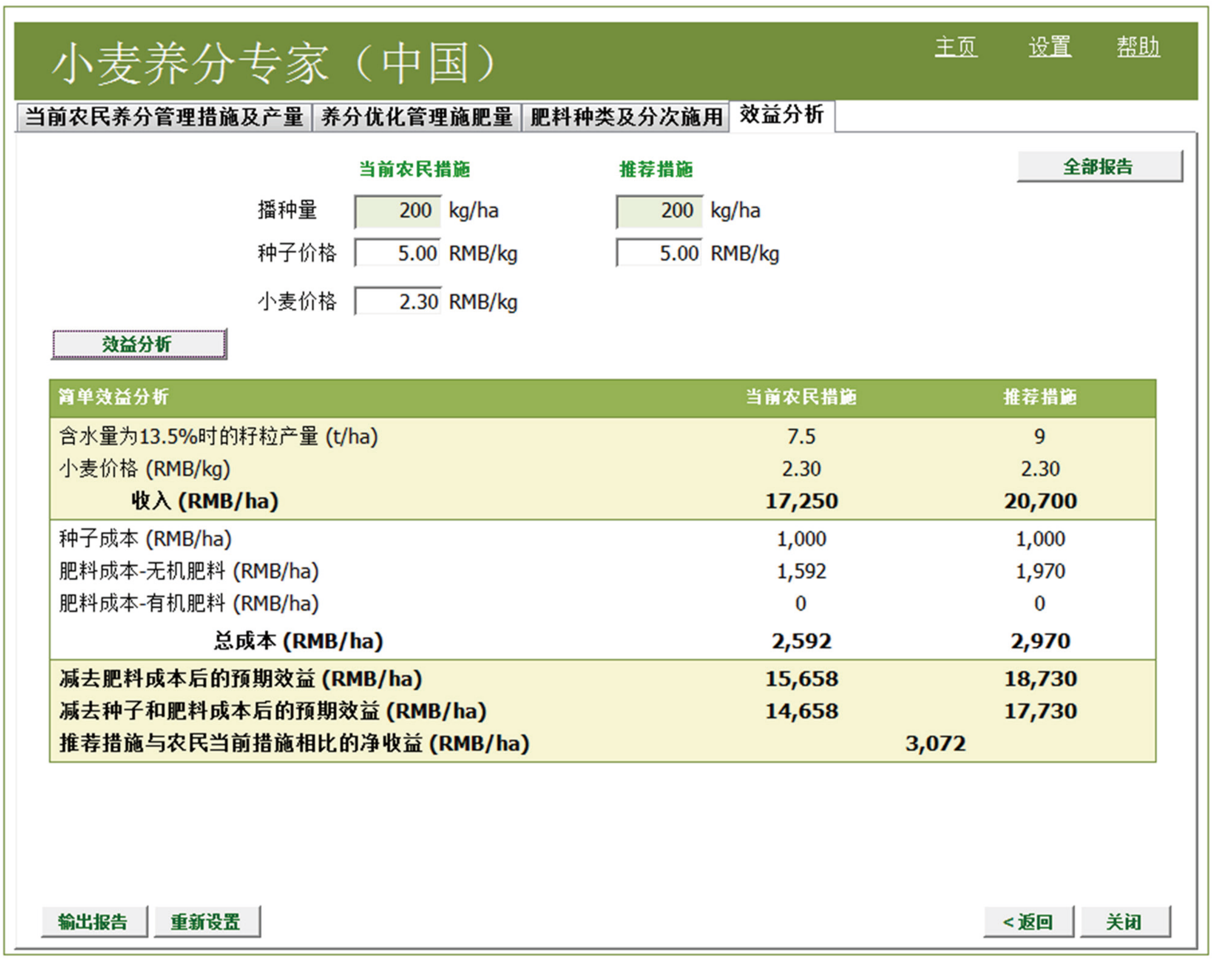
○ 如果钾肥必须一次施用，并且选择的磷肥肥源为复合肥，则不足的钾素由单质钾肥补足。

六、经济效益分析

输入信息：

- 小麦销售价格
- 种子价格
- 化肥价格（从设置栏中用户定义的已有肥料价格估算）

输出信息：比较农民习惯施肥措施与推荐施肥措施的预计成本和收益



小麦养分专家（中国） 主页 设置 帮助

当前农民养分管理措施及产量 | 养分优化管理施肥量 | 肥料种类及分次施用 | 效益分析

全部报告

	当前农民措施	推荐措施
播种量	200 kg/ha	200 kg/ha
种子价格	5.00 RMB/kg	5.00 RMB/kg
小麦价格	2.30 RMB/kg	

效益分析

简单效益分析	当前农民措施	推荐措施
含水量为13.5%时的籽粒产量 (t/ha)	7.5	9
小麦价格 (RMB/kg)	2.30	2.30
收入 (RMB/ha)	**17,250**	**20,700**
种子成本 (RMB/ha)	1,000	1,000
肥料成本-无机肥料 (RMB/ha)	1,592	1,970
肥料成本-有机肥料 (RMB/ha)	0	0
总成本 (RMB/ha)	**2,592**	**2,970**
减去肥料成本后的预期效益 (RMB/ha)	**15,658**	**18,730**
减去种子和肥料成本后的预期效益 (RMB/ha)	**14,658**	**17,730**
推荐措施与农民当前措施相比的净收益 (RMB/ha)	**3,072**	

输出报告 重新设置 < 返回 关闭

效益分析模块比较了农民当前施肥措施和推荐施肥措施预计投入和收益。该分析模块需要用户提供小麦销售价格和种子价格。通常情况下，推荐的小麦播种量为 150 kg/ha。用户可以适当修改播种量，在对应的数据框中输入数值即可。

所有推荐施肥措施成本和收益都是预期的，该值取决于用户定义的肥料、种子和产品价格，并假定目标产量能够实现。

植物营养与肥料学报 2012,18(2): 499 -505
Plant Nutrition and Fertilizer Science

基于作物产量反应和农学效率的推荐施肥方法

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摘要: 当前农民过量和不平衡施用化肥现象严重,导致肥料利用率降低,影响到农田的可持续利用。因此,发展适合我国农业生产特点的养分管理和施肥方法尤为重要。本文介绍了基于作物产量反应和农学效率的推荐施肥新方法,该方法是以改进的 SSNM (Site-specific Nutrient Management) 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可为当地技术推广人员掌握的 Nutrient Expert 推荐施肥专家系统。Nutrient Expert 推荐施肥专家系统在用户回答一些简单问题后就能给出基于作物栽培管理措施的推荐施肥套餐,包括作物种植密度、目标产量、推荐的养分用量及其可选用的物化的肥料用量,同时根据预知的作物生长季节推荐施肥的最佳时间和次数。通过跨区域田间多点验证试验证明,基于作物产量反应和农学效率的推荐施肥方法是一种简单的易于掌握的作物增产增收、提高肥料利用率和保护环境的新方法。

关键词: 产量反应; 农学效率; Nutrient Expert; 推荐施肥
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Approach and decision support system based on crop yield response and agronomic efficiency

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Abstract: Over and imbalanced fertilization by farmers driven by pursuing high yield results in low fertilizer use efficiency, and therefore influences sustainable utilization of farmland. Thus, develop a new tool to better nutrient management and fertilization which is best suitable for China's agriculture is quite urgent. A new approach based on crop yield responses and agronomic efficiency addresses all such concerns. The principles of nutrient management and fertilizer recommendation was based on improved SSNM and QUEFTS model guided nutrient management, and integrated consideration of balanced fertilization of all plant nutrients. The nutrient management principles were developed to consolidate the complex and knowledge intensive information into simple deliverable computer software named "Nutrient Expert" enabling local advisors rapidly implements this technology to ensure cost-effectively field specific guidelines for fertilizer recommendations. The software only requires information that can be easily provided by farmers or local expert. The user will get a package guideline on fertilizer management (and more, such as recommended plant density, attainable yield, the right application time suitable for his local condition) that are tailored to his location and locally-available fertilizer sources after answering a set of simple questions. Multiple-site field validation across larger area demonstrated that the easily grasped new approach based on crop yield responses

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and agronomic efficiency helps in strategizing appropriate management of nutrients leading to better yield and profits, nutrient use efficiency improvement and environmental protection.

Key words: crop yield responses; agronomic efficiency; Nutrient Expert; fertilizer recommendation

为满足日益增加的人口对粮食增长的需求，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[1-4]。研究表明，在华北平原许多地区，农民在冬小麦和夏玉米作物每季的氮肥用量超过 300 kg/hm^2，远远超过达最高产量时的优化施肥量[2,5]。连续过量施氮使华北地区土壤矿质氮高量积累，氮肥利用率显著降低[6]。赵士诚等[3]研究发现河北冬小麦收获后 0—100 cm 土层矿质氮积累达 180 ~ 303 kg/hm^2，且矿质氮积累量随施氮量的增加而增加。冬小麦的氮肥利用率也由上世纪 80 年代的 30% ~ 35% 下降为现在的 10% ~ 20%[7-8]。大量研究证明，高量化肥投入不仅不能带来进一步的产量增加，而且还威胁到生态环境安全，造成地表水或地下水体硝酸盐含量超标，并影响到农田的可持续利用[9]。因此，如何合理养分管理和优化施肥对于保障国家粮食安全、生态环境安全具有重要意义。

国内外在土壤养分管理和推荐施肥方面开展了大量研究，发展了一些推荐施肥的方法，有些方法仍然沿用至今，如地力分级法、目标产量法、肥料效应函数法等等。这些研究方法都可以归结为两大类，一类是以土壤测试为基础的测土推荐施肥方法，另一类是以作物反应为基础的推荐施肥方法，如肥料效应函数法和地上部冠层营养诊断等[10-11]。目前我国指导施肥指标体系仍然沿用上世纪八十年代第二次土壤普查结果[12]，但是我国目前土壤养分状况已今非昔比，在一些土壤测试值很高的土壤上有时仍表现出缺素症状，过去指导施肥的指标体系难以适应当前高投入高产出这种高强度利用农业生产体系的需求。为此，国家农业部 2005 年起启动了"测土配方施肥行动工程"，推动了各地测土推荐施肥工作的开展。然而，对于土壤氮素而言，国内外土壤氮素测试和推荐施氮技术仍然是悬而未决的一个难题，主要是因为它在土壤中的转化过程十分复杂，损失的途径也很多，如氨挥发、反硝化以及过量灌溉和遇到大量降雨而造成的硝酸盐向地下淋洗等，对环境的影响也很大(如对地下水、土壤和水等) 。目前，国际上对于土壤氮的测试和氮肥推荐也没有令人满意的适合各种土壤类型的测试方法、指标和参数。即使对土壤各种营养元素的土壤测试方法都比较满意，在我国主要以小农户为主要经营单元的农业生产体系，也很难做到一家一户依据土壤测试结果推荐施肥。此外，传统施肥较多地基于经验性施肥参数，如养分当季回收利用率，而该参数的获取需要测定植株养分，而我国作物种植区域辽阔，获取不同区域上的参数需要大量的人力、物力和财力，且很难给出基于不同区域上的参数，造成目前多以经验指导施肥，科学的区域性参数较少。因此，寻求一种能适合我国农业生产体系的养分管理和推荐施肥方法尤为迫切。

1 基于作物产量反应和农学效率的养分管理和施肥推荐原则

作物施肥后主要通过作物产量高低来表征土壤养分供应能力和作物生产能力，因此依据作物产量反应来表征作物的营养状况是更为直接的评价施肥效应的有效手段。该方法把土壤养分供应看作一个"黑箱"，用不施该养分地上部的产量或养分吸收来表征，因此解决了困扰广大科学工作者的土壤氮素供应问题 。国际植物营养研究所(IPNI) 目前在中国、印度、菲律宾等亚洲一些主要以小农户为主要经营单元的国家和地区开展了基于作物产量反应和农学效率的小麦、玉米和水稻养分管理和推荐施肥研究。该养分管理和推荐施肥原则主要是在 Witt 等[13]水稻养分管理的 SSNM(Site-specific Nutrient Management) 原则基础上改进，并利用 QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) 模型在分析大量的来源于不同试验地点作物养分吸收和产量关系的基础上进行参数调整而成[2,14-15]，在此基础上结合不同作物种植体系和管理方式发展而成适合当地生产条件的养分管理和推荐施肥系统。该系统在中国的形成主要以 IPNI 在中国的多年多点田间试验为基础，根据不同地区作物反应和农学效率进行调整，从而根据不同试验地点的不同生态条件进行有针对性的推荐施肥。该养分管理方法的主要创新之处在于应用 QUEFTS 模型对来自我国 2001 ~ 2010 年期间多点的田间试验产量和养分吸收数据进行了模拟和矫正，得出我国玉米和小麦种植区一定目标产量下的养分最佳吸收曲

线,避免了较少数据点带来的因养分缺乏、过量或信息量少情况下的偏差,而且该养分最佳吸收曲线包含了我国主要玉米或小麦种植区生产中应用的品种和环境条件信息,具有一定的普遍性(图 1) 。其特点和目标是有效利用了来自于土壤、作物残体、有机肥以及灌溉水等土壤基础养分供应(土壤基础养分供应主要由不施某种养分小区的养分吸收或产量来衡量) ,保证氮、磷、钾和其他中、微量元素的充足供应,同时避免作物对某种养分的奢侈吸收,减少土壤肥力耗竭,保证农民增产增收,有效防止因过量施肥导致的潜在环境危险。对于氮素养分推荐施肥,主要依据作物产量反应和农学效率(施氮量 = 施氮的产量反应/氮素农学效率,施氮的产量反应由施氮和不施氮小区的产量差求得) ,而对于磷、钾养分推荐,主要基于产量反应和一定目标产量下作物的移走量给出施肥量(施磷或施钾量 = 作物产量反应施磷或施钾量 + 作物收获物移走量) ,作物养分移走量主要依据 QUEFTS 模型求算的养分最佳吸收量来求算。如果作物施肥无反应,则给出根据 QUEFTS 模型求算的基本养分移走量。氮、磷、钾养分推荐主要考虑作物种植体系,并考虑上季作物残效。中、微量元素则以土壤养分测试数据为依据进行适当补充。

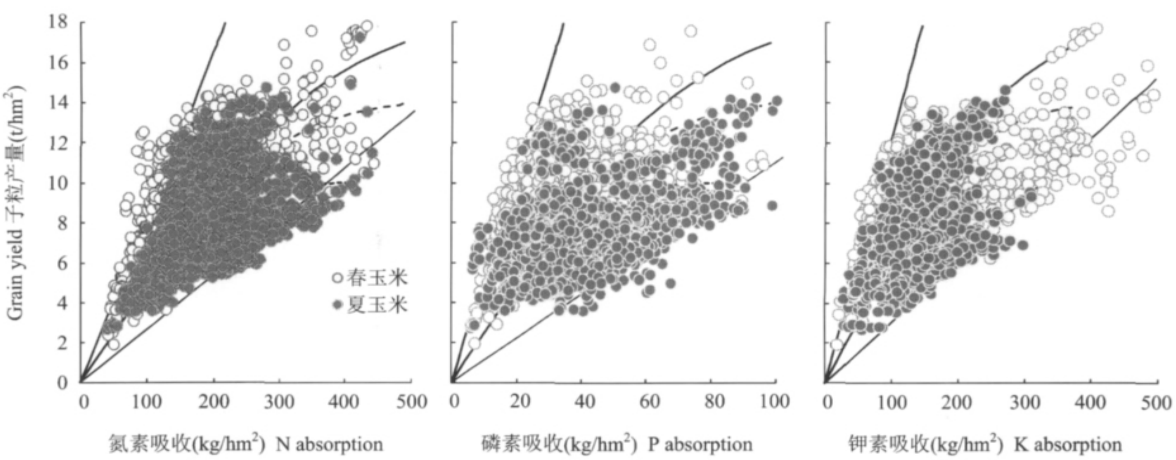

图 1 应用 QUEFTS 模型模拟的玉米氮磷钾养分吸收

Fig. 1 Nitrogen, phosphorous and potassium uptake by maize plant simulated by QUEFTS model

2 专家系统用户界面介绍

基于以上养分管理原则,应用计算机软件技术发展成为作物养分管理专家系统(Nutrient Expert) (图 2,以玉米为例) 。Nutrient Expert 专家系统主要通过农民或当地农技推广专家提供一些简单的作物栽培管理历史信息,系统利用后台已有的数据库就能生成基于农户不同个性信息的包括栽培管理措施的施肥营养套餐,如推荐的种植密度(玉米) 、可获得的目标产量和肥料最佳施用时间和次数等,帮助农民实现增产增收的目标。需要农民或当地农技推广人员提供的栽培管理信息包括:

当前农民的产量和养分管理措施包括农民目前的种植密度,用于优化栽培措施和进行经济效益比较分析;

用于评估目标产量的作物生长环境,在有灌溉条件和雨养条件下由于作物可预知达到的目标产量是不一样的,因此给出的施肥总量和生育期运筹方案有所不同;

土壤肥力指标(如土壤质地和颜色,肥料投入历史) 或作物对化肥氮、磷、钾施用的产量反应,土壤肥力指标调查主要用于在没有氮、磷、钾施肥反应信息的条件下,可以根据后台数据库评估作物施肥后的产量反应,后台数据库主要依据过去十年在中国开展的田间试验为依据;

当季或上季作物施肥包括有机肥和化肥、秸秆或残留物处理方式,用于从作物轮作周期角度考虑养分带入和移走量,用于调整当季作物养分推荐量。

在回答了以上一些简单问题后,用户将得到适合该特定地块和特殊生长环境的肥料养分管理套餐,推荐的肥料用量可以依据用户已有的肥料产品来进行用量折算,不受肥料产品限制,如农户只有尿素和复合肥,那么系统就根据农户已有的肥料储备进行推荐。该系统还提供了一个简单的与农民习惯施肥对比的优化施肥等管理措施的经济效益分析。Nutrient Expert 专家系统营养套餐基本内容包括:

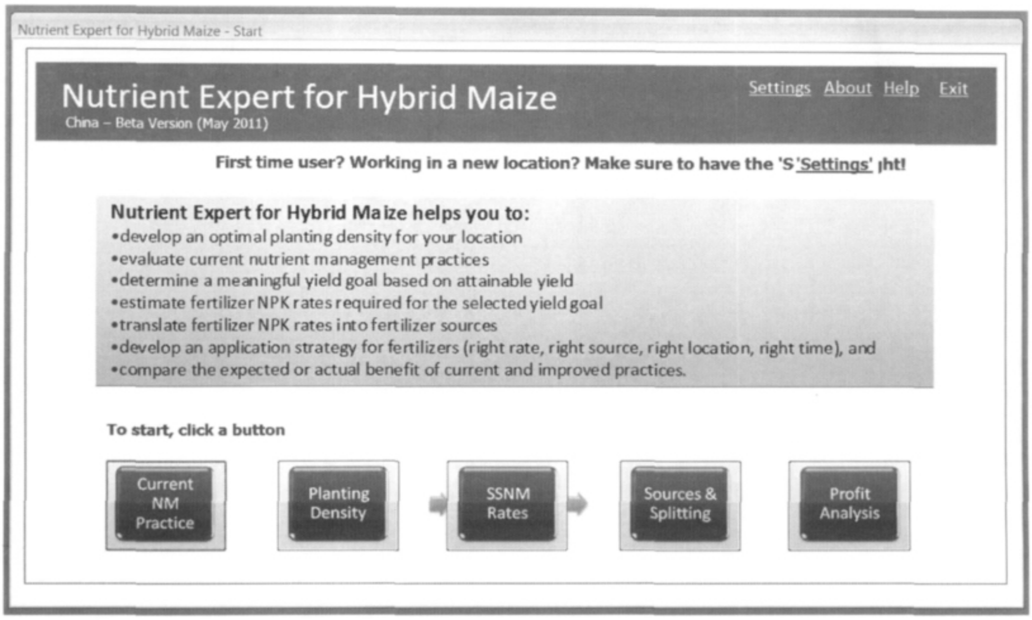

图 2 Nutrient Expert 玉米专家系统用户界面

Fig. 2 User interface of Nutrient Expert Decision Support System for maize

制定特定地块的最佳种植密度(仅对于玉米而言);

评价农户当前的养分管理措施,用于优化养分管理措施和经济效益分析;

确定当地气候条件下能够达到的目标产量;

给定基于一定目标产量的氮、磷、钾等大、中微量元素养分用量及其基于农户可用的肥料实物量;

依据作物养分吸收规律确定 4R 养分管理策略(如最佳肥料用量、最佳施用位置和最佳施用时间等)(图 3,以玉米为例);

与农民习惯施肥对比的预期推荐施肥效益(图 4,以玉米为例)。

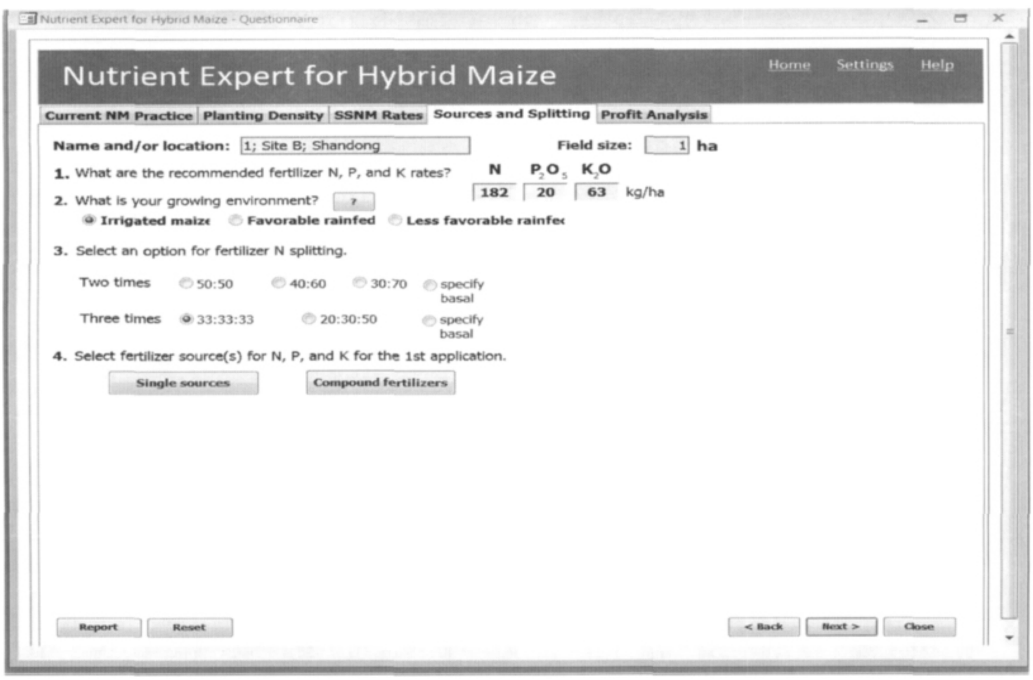

图 3 Nutrient Expert 玉米专家系统用户界面的肥料种类和分次施肥推荐

Fig. 3 Fertilizer sources and recommended splitting guided through Nutrient Expert software for maize

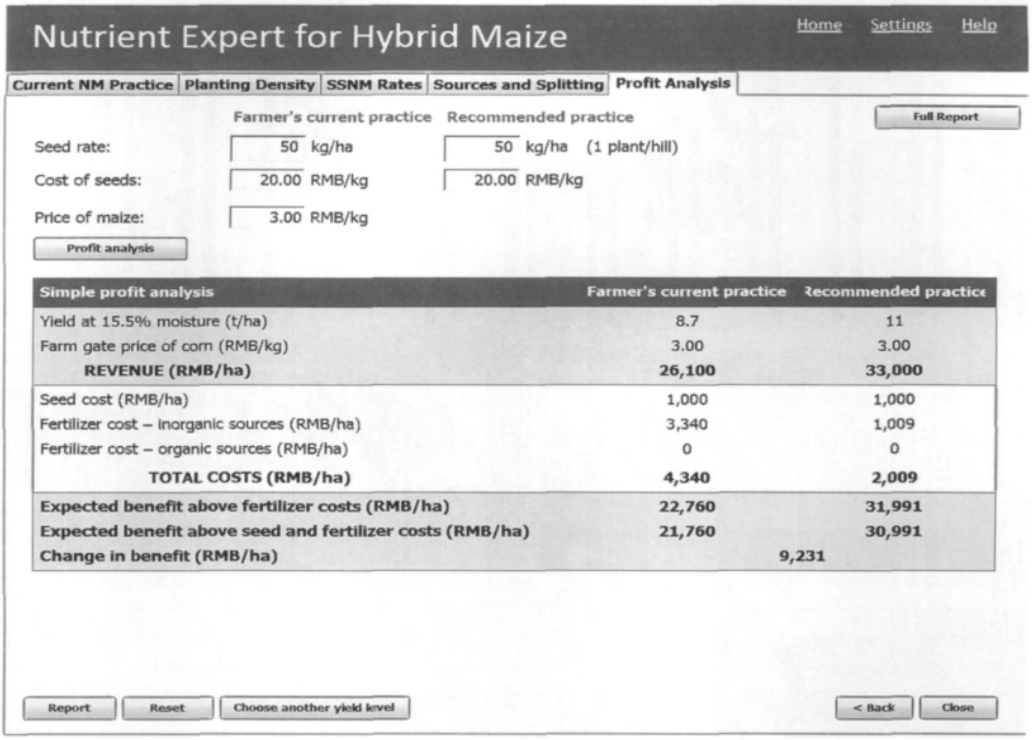

图 4 Nutrient Expert 玉米专家系统经济效益分析界面

Fig. 4 Interface of profit analysis of Nutrient Expert software for maize

3 Nutrient Expert 专家系统推荐施肥实践

应用 Nutrient Expert 专家系统于 2010 年在河北(33 户)、山东(25 户)、山西(11 户)、河南(60 户)四个省市 129 个农户上进行玉米推荐施肥(OPT－NE),同时以农民习惯施肥(FP)和当地推荐施肥(主要以测土施肥为依据,OPT－local)为对照。田间验证结果表明,与农民习惯施肥和当地推荐施肥比较,基于 Nutrient Expert 专家系统推荐施肥虽然在产量和经济效益上没有显著差别,但是具有一定增产和提高经济效益趋势(图 5)。更为重要的是,基于 Nutrient Expert 专家系统比当地推荐施肥节约氮肥 26～31 kg/hm^2(或 11.4%～11.5%),比农民习惯施肥节约氮肥 82～106 kg/hm^2(或 42.0%～55.6%),同时平衡了磷、钾养分,因此虽然降低了氮肥用量,但是并没有降低产量(表 1)。养分表观平衡结果表明,基于 Nutrient Expert 专家系统推荐施肥氮磷钾养分基本保持平衡或略有盈余,氮磷钾平衡分别为 N 40～67 kg/hm^2、P_2O_5 4～19 kg/hm^2 和 K_2O 21～42 kg/hm^2,而当地推荐施肥盈余较多,氮磷钾平衡分别为 N 99～171 kg/hm^2、P_2O_5 15 kg/hm^2 和 K_2O 43～47 kg/hm^2,农民习惯施肥表现为氮素盈余较多,磷、钾亏缺,氮磷钾平衡分别为 N 123～200 kg/hm^2,P_2O_5 －43～17 kg/hm^2 和 K_2O －26～23 kg/hm^2。虽然农民习惯施肥或当地推荐施肥氮素用量过高,但是由于养分施用不平衡并没有进一步提高产量,反而增加了因氮素过量施用而带来的环境风险[2,5]。值得提出的是,该方法在优化用量的同时,还优化了其他养分管理措施,如肥料的施用次数和施肥方法等。在我们试验的大部分地区农民在玉米上只一次施撒施肥料,我们的优化施肥是 1～2 次施肥并有些地区能够施肥后覆土以减少氮肥的挥发损失,提高氮肥利用率。

以上实践证明,Nutrient Expert 推荐施肥专家系统是一种简便易行的增产增收、提高肥料利用率和保护环境的养分管理和推荐施肥方法。

基于 Nutrient Expert 推荐施肥系统已经成为菲律宾和印度尼西亚农业部推荐施肥的官方推荐方法,在印度的水稻、小麦和玉米种植区已经开展相应的田间验证工作,并已被一些种子公司和肥料企业推荐施肥所采纳[16]。 相信该方法不仅适合于以

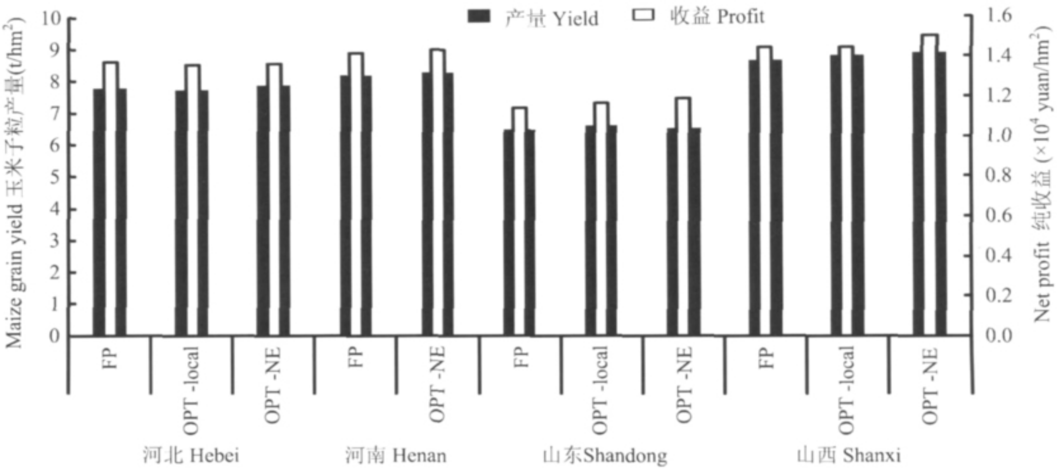

图 5 基于 Nutrient Expert 推荐施肥的玉米子粒产量和经济效益

Fig. 5 Grain yield and net profit with Nutrient Expert based fertilizer recommendation

[注(Note): FP—农民习惯施肥 Farmer's practice; OPT-local—当地推荐施肥 Local fertilizer recommendation; OPT－NE—基于Nutrient Expert 专家系统推荐施肥 Nutrient Expert based fertilizer recommendation. 图中不同处理之间差异不显著($P>0.05$) There is no significant differences among treatments.]

表 1 不同养分管理方式对养分表观平衡的影响

Table 1 Apparent nutrient balance as influenced by different nutrient management practices

试验地点 Experimental site	农户数 Observation No.	处理 Treatment	平均施肥量 Mean fertilizer appl. rate (kg/hm²)			作物养分移走量 Crop nutrient removal (kg/hm²)			养分平衡 Nutrient balance (kg/hm²)		
			N	P_2O_5	K_2O	N	P_2O_5	K_2O	N	P_2O_5	K_2O
河北 Hebei	33	OPT-NE	135	52	60	84	33	18	51	19	42
		FP	235	6	0	83	31	17	152	－25	－17
河南 Henan	60	OPT-NE	145	51	61	105	47	42	40	4	19
		FP	251	4	5	100	47	31	151	－43	－26
山东 Shandong	25	OPT-NE	140	51	61	73	36	21	67	15	40
		OPT-local	240	51	61	69	36	18	171	15	43
		FP	271	52	42	71	35	19	200	17	23
山西 Shanxi	11	OPT-NE	144	53	51	102	45	30	42	8	21
		OPT-local	200	60	75	101	45	28	99	15	47
		FP	226	61	25	103	44	29	123	17	－4

注(Note): 养分表观平衡＝施肥量－子粒养分移走量 Apparent nutrient removal = Fertilizer application rate － Nutrient removal by grain. FP—农民习惯施肥 Farmers' practice; OPT-local—当地推荐施肥 Local fertilizer recommendation; OPT－NE—基于 Nutrient Expert 专家系统推荐施肥 Nutrient Expert based fertilizer recommendation.

家庭为主要经营单元的小农户生产体系，而且适合区域和大规模经营农业生产体系。

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Estimating nutrient uptake requirements for wheat in China

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ABSTRACT

Estimating balanced nutrient requirement for wheat (*Triticum aestivum* L.) in China is essential to manage nutrient application more effectively for increasing crop yields and reducing risk of negative environmental impact. Datasets from 2000 to 2011 dealing with nitrogen (N), phosphorus (P) and potassium (K) treatments across the winter and spring wheat growing regions in China were collected to assess the relationship between grain yield and nutrient uptake, and to estimate N, P and K optimal nutrient requirements for a target yield using the QUEFTS (Quantitative Evaluation of the Fertility of Tropical Soils) model. In the QUEFTS model, two boundary lines described the minimum and maximum internal efficiencies (IEs, kg grain per kg nutrient in above-ground plant dry matter) of N, P and K. The minimum and maximum IEs for wheat were 28.8 and 62.6 kg grain per kg N, 98.9 and 487.4 kg grain per kg P, and 23.0 and 112.9 kg grain per kg K. The QUEFTS model predicted a linear–parabolic–plateau curve for balanced nutrient uptake with target yield increasing. The linear part continued until the yield was approximately at 60–70% of the potential yield, and 22.8 kg N, 4.4 kg P and 19.0 kg K were required to produce 1000 kg grain. The corresponding N:P:K ratio was 5.18:1:4.32, and the corresponding IEs were 43.9, 227.0 and 52.7 kg grain per kg N, P and K, respectively. The QUEFTS model simulated balanced N, P and K removal by 1000 kg grain were 18.3, 3.6 and 3.5 kg, respectively, with a N:P:K ratio of 5.08:1:0.97. Approximately 80%, 82% and 18% of N, P and K in total above-ground plant material were presented in the grain and removed from the field. The relationship between grain yield and nutrient uptake was also estimated to suggest fertilizer application avoiding excess or deficient nutrient supply. Field experiment validation confirmed that the QUEFTS model could be used as a practical tool for the *Nutrient Expert* decision support system to make fertilizer recommendation.

1. Introduction

Wheat (*Triticum aestivum* L.) is an important cereal crop in China, and it is usually grown in rotation with maize (*Zea mays* L.) in North Central China, with rice (*Oryza sativa* L.) in the middle and lower reaches of the Yangtze River, and winter and spring wheat are both grown in Northwest China. The yield has been improved in the last decade, but the total production has been stagnant and even decrease due to the planting area changing. Fertilizer application has played a dominant role in increasing yield; however, current fertilizer management approaches do not usually apply in balance to match crop demand, resulting in waste of fertilizer resources and low nutrient use efficiency (Zhang et al., 2009). To improve the efficiency of fertilizer inputs, a computer software program named *Nutrient Expert* (NE) is a new decision support system to make fertilizer recommendation. This NE system is based on improved site-specific nutrient management (SSNM) and the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model to guide fertilizer application, with integrated consideration of balanced inputs of all plant nutrients (He et al., 2012; Pampolino et al., 2011, Pampolino et al., 2012; Satyanarayana et al., 2011).

SSNM could closely match nutrient supply and demand within a specific field for splitting and timing of fertilizer application, as well as use of the chlorophyll meter or leaf color chart as an indicator to change crop nitrogen (N) demand in a particular season (Dobermann et al., 2004). Strategies for SSNM that assess crop

Abbreviations: HI, harvest index; IE, internal efficiency; K, potassium; N, nitrogen; NE, nutrient expert; OPT, optimal practice treatment; P, phosphorus; RE, recovery efficiency; RIE, reciprocal internal efficiency; SSNM, site-specific nutrient management.

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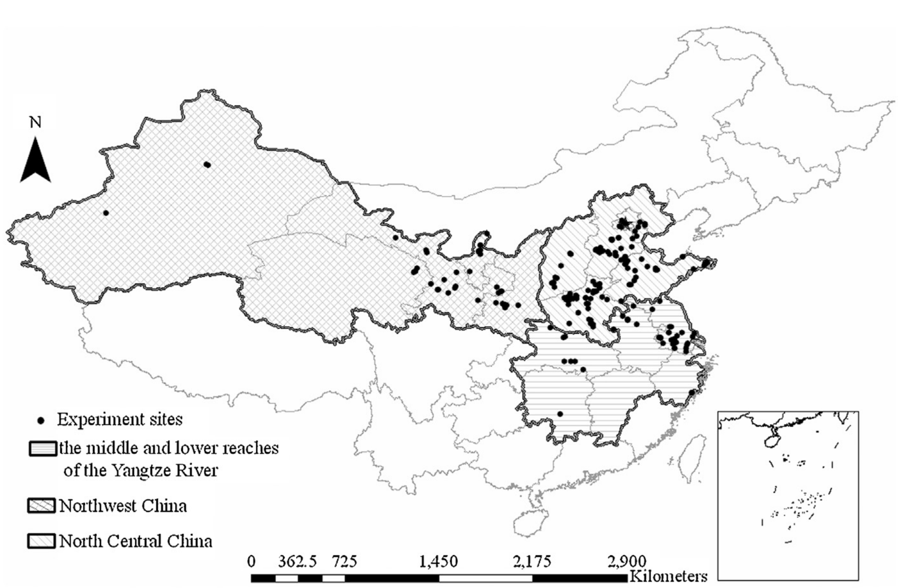

Fig. 1. Geographical distribution of studied locations in North Central China, the middle and lower reaches of the Yangtze River, and Northwest China. The black solid lines are the boundaries of each region.

nutrient requirements, indigenous nutrient supply and recovery efficiency (RE, the fraction of nutrient uptake in above-ground biomass to the nutrient applied) of applied fertilizer could be used to increase crop yield and nutrient use efficiency. These principles to determine field- and season-specific fertilizer application have been applied successfully on rice (Buresh and Witt, 2007; Witt et al., 2007; Buresh, 2009), wheat (Khurana et al., 2008) and maize (Witt et al., 2009).

However, there were many uncertainties about N, phosphorus (P) and potassium (K) nutrient requirements of crops because the internal efficiency (IE, the amount of grain yield produced per unit of nutrient accumulated in above-ground plant dry matter) varied greatly depending on the very broad ranges of soil, nutrient supply, crop management and climate conditions encountered, making it difficult to extrapolate to small farmers' field (Van Duivenbooden et al., 1996). Therefore, the SSNM approach advocated that more generic and quantitative approaches such as some simulation models should be established to estimate the relationships between grain yield and nutrient uptake to help make fertilizer recommendations (Witt et al., 1999; Maiti et al., 2006).

The QUEFTS model then was selected to resolve this problem, since it took into account the interactions of N, P and K, which was the most important and different characteristic from other models (Janssen et al., 1990). The QUEFTS model provided a generic empirical relationship between grain yield and nutrient accumulation in plants following a linear-parabolic-plateau model, also used two linear boundaries to describe the range between maximum nutrient accumulation (a) and maximum nutrient dilution (d) situations (Smaling and Janssen, 1993; Witt et al., 1999; Witt and Dobermann, 2004). The QUEFTS model has been applied on rice in Asia, India and West Africa (Witt et al., 1999; Haefele et al., 2003; Das et al., 2009; Buresh et al., 2010), wheat in India and China (Pathak et al., 2003; Liu et al., 2006), and maize in Africa, Nigeria, Kenya, Nebraska, Southeast Asia and China (Janssen et al., 1990; Saidou et al., 2003; Liu et al., 2006; Tabi et al., 2008; Tittonell et al., 2008; Setiyono et al., 2010). It provided a very practical tool for site-specific nutrient management concepts for major crops (Dobermann et al., 2002; Khurana et al., 2008; Witt et al., 2008; Setiyono et al., 2010).

A previous study of the QUEFTS model on wheat in China was published in 2006 (Liu et al., 2006), and used a smaller region mainly in Huang-huai-hai plain and a smaller dataset only from 1985 to 1995, with yield potential set at 10,000 kg/ha for wheat. However, in this study, datasets were different from Liu's that covered a wide range of wheat yield, soil types and climate, including more recent data from the year 2000 to 2011. The soil types and climate covered North Central China, the middle and lower reaches of the Yangtze River and Northwest China. The crop varieties, fertilizer utilization and environmental adaptability were very different from those in 1985–1995, which were the most important influencing factors on nutrient uptake. These datasets allowed the estimation of new relationships between grain yield and nutrient uptake, also as a support to the background database of NE for wheat as we mentioned above. Therefore, the objective of this study was to estimate the optimal nutrient requirements of N, P and K uptake for a specific target yield using the QUEFTS model.

2. Materials and methods

2.1. Data source

Datasets for grain yield, N, P and K uptake in above-ground plant dry matter, harvest index (HI, kg grain per kg total above-ground dry matter) and fertilizer application were compiled from published literature from the year 2000 to 2011 in China, and published or unpublished datasets from the International Plant Nutrition Institute (IPNI) China Program database. The datasets contained many different nutrient management practices to establish a wide range of nutrient dilution and accumulation situations, including farmers' practice, optimal practice treatment (OPT), long-term field experiments and different rates of fertilizer treatments across wheat-growing environments of China, encompassing North Central China, the middle and lower reaches of the Yangtze River and Northwest China (Fig. 1). The data included a wide range of soil types and climate conditions, with a large variation in soil properties (Tables 1 and 2). The wheat varieties in the experiments were all commonly used in local high yield production and highly represent the great variation in the wheat production area.

2.2. Model background

The QUEFTS was originally developed by Janssen et al. (1990), affirmed that the yield was a combined function of N, P and K, and described the relationship between grain yield and nutrient uptake following four steps: (1) assess the potential indigenous

Table 1
Climate characters of experimental sites for wheat production in three regions of China.

Region	Province	season	n[a]	Precipitation (mm)	Latitude	Longitude	T_{min}[b]	T_{max}[c]
NC[d]	Hebei	Winter	1305	350–500	38.04	114.51	−8	33
	Henan	Winter	2009	500–900	34.75	113.62	−3	33
	Shanxi	Winter	856	350–700	36.09	111.52	−4	28
	Shandong	Winter	1161	550–950	36.67	116.99	−3	30
	Beijing	Winter	62	550–650	39.90	116.41	−10	33
MLYR[e]	Jiangsu	Winter	616	800–1200	32.06	118.80	3	30
	Hubei	Winter	160	750–1500	30.59	114.31	−4	35
	Anhui	Winter	151	750–1700	31.82	117.23	−1	30
	Hunan	Winter	11	1200–1750	28.23	112.94	4	35
NW[f]	Shaanxi	Winter	312	350–650	34.26	108.94	−10	28
	Ningxia	Spring	232	200–600	38.47	106.26	−9	25
	Gansu	Spring	599	100–300	36.06	103.83	−19	36
	Xinjiang	Winter	11	100–300	43.79	87.63	−20	33

[a] n = number of the observations.
[b] T_{min} = minimum temperature.
[c] T_{max} = maximum temperature.
[d] NC = North Central China.
[e] MLYR = the middle and lower reaches of the Yangtze River.
[f] NW = Northwest China.

nutrient supply based on the soil chemical character; (2) calculate the actual uptakes of N, P and K based on the potential supplies of N, P and K. Nutrients are compared in pairs, for an example, the relationship between the actual uptake and the potential supply of N is calculated twice: one is depending on the potential supply of P, and another is depending on the potential supply of K. Likewise, the actual P uptake is depending on the potential supply of N and the potential supply of K, and the actual K uptake is depending on the potential supply of N and the potential supply of P; (3) identify the yield ranges as functions of the actual uptakes of N,

Table 2
Soil properties of experimental sites for wheat production in three regions of China.

Region	Province	Main Soil type	pH	Organic matter (g/kg)	Alkali- hydrolysable N (mg/kg)	Olsen P (mg/kg)	NH_4OAc-K (mg/kg)
NC[a]	Hebei	Haplic Luvisol; Eutric Fluvisol; Dystric Fluvisol; Eutyic Cambisol	7.8–8.6	8.0–19.3	45.2–99.8	3.6–53.2	67.9–157.5
	Henan	Haplic Luvisol; Eutric Fluvisol; Calcic Vertisol; Dystric Fluvisol	6.1–8.4	4.0–20.5	43.6–113.0	3.1–67.5	54.1–152.5
	Shanxi	Haplic Luvisol; Dystric Fluvisol	7.4–8.2	11.2–18.0	46.4–88.1	13.1–16.5	95.0–201.5
	Shandong	Haplic Luvisol; Eutric Fluvisol; Gleyic Cambisol	5.5–8.5	6.8–18.9	37.5–114.7	8.4–70.2	53.0–187.8
	Beijing	Eutric Fluvisol; Dystric Fluvisol	7.8–8.5	6.1–26.7	49.7–78.0	12.0–41.9	87.7–99.5
MLYR[b]	Jiangsu	Haplic Luvisol; Hydragric Anthrosol; Eutric Fluvisol; Umbric Gleysol; Calcic Vertisol	7.3–8.2	9.2–35.0	42.3–198.8	2.45–107.9	42.4–180.8
	Hubei	Haplic Luvisol; Hydragric Anthrosol	6.6–7.3	11.0–12.3	78.8–83.7	16.2–33.3	51.1–152.0
	Anhui	Haplic Luvisol; Hydragric Anthrosol; Eutric Vertisol	5.3–8.3	11.9–18.2	50.4–103.5	13.0–38.5	111.6–270.1
	Hunan	Haplic Acrisol	4.9–5.7	5.4–8.9	50.4–79.3	4.7–10.8	104.2–122.6
NW[c]	Shaanxi	Cumulic Anthrosol; Cumuli-Haplic Kastanozem	7.4–8.6	5.7–17.1	35.5–115.4	2.2–61.4	93.0–191.0
	Ningxia	Calcaric Fluvisal; Eutric Fluvisol	7.5–8.1	10.7–15.9	50.8–70.4	9.9–31.8	144.2–226.7
	Gansu	Haplic Podzol; Gelic Histosol	7.7–8.8	12.9–19.3	48.2–234.2	16.3–37.6	130.3–233.8
	Xinjiang	Luvic Gypsisol; Calcaric Cambisol	7.6–8.1	6.4–8.9	55.2–80.4	3.9–5.7	220.4–288.5

[a] NC = North Central China.
[b] MLYR = the middle and lower reaches of the Yangtze River.
[c] NW = Northwest China.

Table 3
Rates of fertilizer application in optimal practice treatment (OPT).

Province	Fertilizer application (kg/ha)		
	N	P	K
Hebei	135(130–150)[a]	23(22–24)	50(40–58)
Henan	150(140–170)	32(29–34)	62(50–66)
Shandong	140	34	58(50–66)
Shanxi	137(125–140)	29	65(50–66)

[a] Data in parentheses indicates the range of fertilizer application.

P and K determined in Step 2 at the situations of maximum accumulation (where the nutrient is sufficient supply) and maximum dilution (where the nutrient is deficient supply); (4) estimate the actual yield based on the three yield ranges (one range each for N, P and K) identified under Step 3 and anticipated interactions between N, P and K (Liu et al., 2006). So in the QUEFTS model, two boundary lines should first be determined, and the QUEFTS model could then simulate a liner-parabolic-plateau curve for estimating optimal nutrient uptake used a solver module in Microsoft Office Excel.

For more details about the QUEFTS model, please refer to the original Janssen et al. (1990) and to Liu et al. (2006).

2.3. Model validation

The OPT for wheat in Hebei (32 plots), Henan (50 plots), Shandong (30 plots) and Shanxi provinces (10 plots) were conducted in 2010–2011 to validate the QUEFTS model. These four provinces were all in North Central China and wheat was the main crop production. Wheat was sown at the beginning of October and harvested in mid-June of the following year. The NE for Wheat decision support system was used to recommend fertilizer application based on the QUEFTS model and applied best management practices through the whole growth period. The fertilizer N recommended by NE was estimated from the yield response to applied N fertilizer and agronomic efficiency of N, and fertilizer P and K were determined from the target yield and yield response combined with optimal reciprocal internal efficiency (RIE, kg nutrient uptake in above-ground plant dry matter per ton grain produced) and nutrient balance to sustain soil fertility, i.e. P and K removal should be return back to the soil (Chuan et al., 2013; He et al., 2012), which was simulated by the QUEFTS model. The yield response to N, P or K is the yield gap between NPK plots that received ample nutrients and omission plots when one of the nutrients is omitted. The agronomic efficiency of N, P or K is the yield increase per unit of fertilizer N, P_2O_5 or K_2O applied. Urea was applied two splits or three splits depending on soil fertility or expected yield response to N (Pampolino et al., 2012), while P and K fertilizers were both broadcasted and incorporated as basal before seeding. The rates of fertilizer application were listed in Table 3. Irrigation and other cultural practices were applied using the best local management.

At harvest, three $1 \times 1\,m^2$ from a location in the middle of each plot were harvested manually to determine straw and grain yield. Harvested straw and grain samples were oven-dried at 60 °C for determination of dry matter weight. Subsamples of straw and grain were digested with H_2SO_4–H_2O_2 and N, P, and K concentration were measured using the Kjeldahl method, vanadomolybdate yellow color method, and flame spectrophotometers, respectively (Chinese Society of Soil Science, 2000). The total nutrient uptake of N, P and K were calculated as the products of the nutrient concentration multiply the plant dry weight.

The two statistical formulas of root mean square error (RMSE) and normalized-RMSE (n-RMSE) were used to evaluate the QUEFTS model and the deviation between the measured and simulated data. The deviation statistics were defined as follows:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{i=1}^{n}(s_i - m_i) \wedge 2}{n}} \quad (1)$$

$$\text{Normalized RMSE} = \frac{\mathrm{RMSE}}{\bar{m}} \quad (2)$$

while s_i and m_i were the simulated and measured values, respectively, n was the number of data, and $\bar{m}$ was the mean of measured data. The RMSE measured the mean discrepancy between the simulated and measured data with the same unit, and the n-RMSE removed the unit and allowed comparison among values with different units (Liu et al., 2011a).

3. Results and discussion

3.1. Characteristics of nutrient uptake

The average grain yield (adjusted to 0.135 g water g^{-1} fresh weight) of wheat (Table 4) was 5 950 kg/ha during the 2000–2011 periods. The range was from 280 kg/ha (from a long-term field experiment) to 12 000 kg/ha (from an OPT, with balanced N, P and K, and best management) with N application rates varying from 0 to 750 kg/ha, P from 0 to 137 kg/ha, and K from 0 to 249 kg/ha. However, the average N, P and K application rates were 172, 44 and 75 kg/ha, respectively. These values seemed reasonable because the datasets collected included farmer's practice, OPT, and omission plots, so they reflected more situations than only the actual status of farmers' fertilizer application in China. The HI ranged from 0.18 to 0.69 with an average of 0.44, which was similar to the value mentioned by Ji et al. (2010) in China in the 2000s, and was higher than values in the 1980s and 1990s, which were 0.38 and 0.41, respectively. The average N, P and K mass fractions in grain were 21.2 g/kg, 5.6 g/kg and 4.3 g/kg (oven-dry weight), and in straw were 5.7 g/kg, 1.4 g/kg, and 15.5 g/kg, respectively. The total above-ground N, P and K accumulation ranged from 11 to 398 kg N/ha, 1.9 to 130.7 kg P/ha, and 11 to 438 kg K/ha. The N, P and K nutrient harvest indices (NHI, PHI and KHI, the ratio of nutrient quantity in grain and total above-ground plant) were 0.74, 0.78 and 0.21, respectively, meaning that about 74%, 78% of N and P in above-ground plant presented in the grain, and 79% of K in the straw. Therefore, grain was the primary pool for N and P, and straw for K. The quantities of P and K in the grain removed from the field were used for the assessment of fertilizer P and K replacement requirements to achieve a target yield as well as to maintain P and K in the soil.

3.2. Internal efficiency and reciprocal internal efficiency

The average internal efficiencies (IEs) were 40.1 kg grain per kg plant N, 189.5 kg grain per kg plant P and 55.8 kg grain per kg plant K, equivalent to reciprocal internal efficiencies (RIEs) of 26.4 kg for N, 6.5 kg for P and 22.0 kg for K to produce 1000 kg grain with a N:P:K ratio of 4.06:1:3.38 (Table 5). In the OPT datasets, the IEs for N, P and K were 39.4 kg grain per kg plant N, 182.6 kg grain per kg plant P, 56.4 kg grain per kg plant K, and to produce 1000 kg grain needed 25.9 kg N, 6.8 kg P and 21.0 kg K, respectively. High IEs values were mainly from the omission plots with no N, P or K fertilizer input. The ranges of IEs were narrower for the OPT datasets than for all datasets, but the differences were not significant. Liu et al. (2006) used smaller datasets from 1985 to 1995 and concluded that the average IEs for N, P and K were 40.1 kg grain per kg plant N, 269.1 kg grain per kg plant P, and 43.1 kg grain per kg plant K, equivalent to 25.8 kg for N, 3.7 kg for P, and 23.3 kg for K to produce

Table 4
Characters of nutrient uptake.

Parameter	Unit	n[a]	Mean	SD[b]	Minimum	25%Q[c]	Median	75%Q	Maximum
Grain yield	kg/ha	7517	5950	1850	280	4860	6150	7190	12,000
N rate	kg/ha	7306	172	92	0	138	180	225	750
P rate	kg/ha	7180	44	23	0	36	46	59	137
K rate	kg/ha	7002	75	57	0	0	75	125	249
Harvest Index	kg/kg	2849	0.44	0.07	0.18	0.41	0.45	0.48	0.69
N uptake in grain	kg/ha	2197	118.1	48.1	7.4	86.0	117.4	143.6	349.8
P uptake in grain	kg/ha	1577	30.0	15.0	0.4	18.5	29.2	40.7	87.3
K uptake in grain	kg/ha	1614	24.6	14.5	0.8	15.2	20.8	30.3	111.7
N uptake in straw	kg/ha	2142	38.6	17.9	2.9	27.2	36.9	47.7	143.3
P uptake in straw	kg/ha	1576	8.6	6.5	0.1	3.5	7.3	12.2	44.9
K uptake in straw	kg/ha	1620	101.3	60.4	3.3	53.5	93.2	124.2	132.1
[N] in Grain	g/kg	1990	21.2	3.9	8.5	18.9	20.8	23.0	41.4
[P] in Grain	g/kg	1496	5.6	2.3	1.1	3.6	6.0	7.2	13.5
[K] in Grain	g/kg	1557	4.3	1.8	0.5	3.1	3.9	5.3	15.6
[N] in Straw	g/kg	1869	5.7	1.6	1.4	4.7	5.5	6.6	21.0
[P] in Straw	g/kg	1491	1.4	0.8	0.1	0.6	1.4	1.5	1.9
[K] in Straw	g/kg	1552	15.5	7.9	3.3	8.8	14.8	13.0	19.8
Plant N	kg/ha	3372	161	61.2	11	120.2	160.7	196.4	398
Plant P	kg/ha	2088	41	21.3	1.9	23.2	38.6	54.5	130.7
Plant K	kg/ha	2098	136	74.0	11	81.3	125.8	174.1	438
NHI[d]	kg/kg	2413	0.74	0.08	0.25	0.71	0.76	0.79	0.94
PHI[e]	kg/kg	1594	0.78	0.10	0.29	0.74	0.78	0.85	0.99
KHI[f]	kg/kg	1636	0.21	0.10	0.01	0.14	0.19	0.25	0.52

[a] n = number of observations.
[b] SD = standard deviation.
[c] Q = quartile.
[d] NHI = nitrogen harvest index.
[e] PHI = phosphorus harvest index.
[f] KHI = potassium harvest index.

1000 kg grain in China. The differences between the two studies mainly occurred for P and K. There were several probable reasons for the different results. Firstly, the data Liu et al. (2006) collected were from 1985 to 1995, when wheat varieties may have lower yield and uptake efficiency than the newer cultivars. Secondly, in 2000s, farmer practices and field experiments usually applied more P in the soil than that applied in early years, but not as much K, so plants accumulated more P and less K. As a result, the RIE for P became higher and the RIE for K a little lower. Thirdly, in past years, the irrigation, fertilizer management, pests and diseases control were not as good as current practice, which could result in different IEs values.

3.3. Estimating the optimum nutrient uptake for a specific target yield

The different envelope coefficients for maximum accumulation and maximum dilution in the above-ground plant dry matter of wheat for N, P and K were shown in Fig. 2. For each nutrient, a and d values represented the maximum accumulation (equivalent to the minimum IEs) and maximum dilution (equivalent to maximum IEs) in wheat. The sensitivity of the model to a and d values was tested using the three sets. Set 1, set 2 and set 3 were calculated from excluding the upper and lower 2.5, 5 and 7.5 percentiles of all internal efficiency data as outliers when HI ≥ 0.40. Low HI suggested that diseases, weeds, or insect pests resulted in some yield loss. Like Witt et al. (1999) and Haefele et al. (2003), data with HI < 0.40 was excluded when determining the relationships and internal nutrient efficiencies using the QUEFTS model for wheat in China. The yield potential defined as maximum attainable yield (Liu et al., 2011b; Setiyono et al., 2011), was set at 12,000 kg/ha in North Central China as an example since the yield potential had no effect on the sensitivity testing.

With a and d coefficients derived and the yield potential set, the QUEFTS model could simulate balanced nutrient uptake requirement for N, P and K (the linear-parabolic-plateau curve) assuming under conditions where the yield was not limited by any nutrients and the crop production was managed by the best practices. The nutrient requirements calculated by the QUEFTS model were similar for all three sets (Fig. 2), except at the yield target approaching the yield potential. Since set 1 included a larger range of variability, it was then used to estimate balanced nutrient uptake

Table 5
Internal efficiency (IE, kg grain/kg nutrient) of N, P and K for wheat in China.

Dataset	Parameter	n[a]	Mean	SD[b]	Minimum	25% Q[c]	Median	75% Q	Maximum
All	IE-N[d]	3372	40.1	9.3	11.3	33.7	39.4	45.3	91.8
	IE-P[e]	2088	189.5	98.4	48.4	120.4	151.6	238.5	614.9
	IE-K[f]	2098	55.8	25.7	12.8	36.8	49.3	73.5	185.8
OPT	IE-N	241	39.4	5.6	24.4	35.6	40.0	42.5	54.3
	IE-P	201	182.6	105.6	83.1	112.2	130.9	234.1	602.0
	IE-K	238	56.4	22.2	14.3	41.1	50.1	79.4	145.2

[a] n = number of observations.
[b] SD = standard deviation.
[c] Q = quartile.
[d] IE-N = internal efficiency of nitrogen.
[e] IE-P = internal efficiency of phosphorus.
[f] IE-K = internal efficiency of potassium.

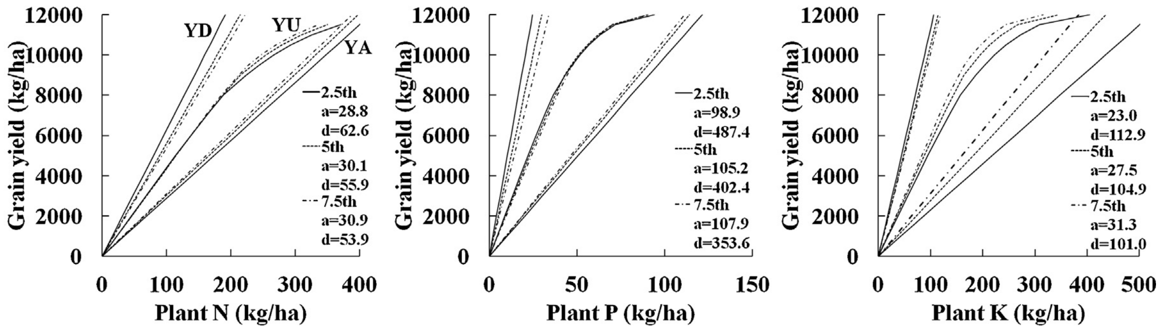

Fig. 2. Yield of wheat in relation to plant nutrient uptake at different sets of constants *a* and *d*, calculated by excluding the upper and lower 2.5 (Set 1), 5 (Set 2) and 7.5 percentiles (Set 3) of all internal efficiency data (HI ≥ 0.40). YD, YA and YU are the maximum dilution, maximum accumulation and balanced uptake of N, P and K in above-ground plant dry matter, respectively. The yield potential was set at 12,000 kg/ha as an example.

and the relationship between grain yield and nutrient accumulation. The slope coefficients of set 1 for *a* and *d* were 28.8 and 62.6 kg grain per kg N, 98.9 and 487.4 kg grain per kg P, and 23.0 and 112.9 kg grain per kg K, respectively. The QUEFTS model predicted that the balanced nutrient accumulation required to produce 1000 kg grain was 22.8 kg N, 4.4 kg P and 19.0 kg K, respectively, when the yield reached about 60-70% of potential yield. The N:P:K ratio was 5.18:1:4.32. The corresponding optimal IEs were 43.9 kg grain/kg N, 227.0 kg grain/kg P and 52.7 kg grain/kg K for balanced nutrition. The RIEs simulated by the QUEFTS model were only for the linear portion of the predicted balanced uptake line, so lower than the values derived from the data collected in Section 3.2 we described. This was confirmed by the increase as target yield increased above 60–70% of the yield potential (Buresh et al., 2010).

Mao (2003) studied that yield potential ranged from 6,000 to 12,000 kg/ha for wheat. However, regardless of the yield potential, the N:P:K ratio in the plant required to produce 1000 kg grain in the linear part of the response curve was always the same (Fig. 3a–c).

Grain nutrient removal could be simulated by the QUEFTS model (Setiyono et al., 2010). It could help to guide fertilizer application where P and K removed in the grain should be returned back to the soil by fertilizer to avoid nutrient depletion. The constants of *a* and *d* for grain nutrient removal were calculated from grain nutrient-IE (kg grain per kg nutrient in grain removed) and excluded the upper and lower 2.5 percentiles (HI ≥ 0.40). The results showed that the balanced grain nutrient removal curve was very similar to the balanced nutrient requirement for total above-ground plant under different yield potentials from 6,000 to 12,000 kg/ha (Fig. 3d–f). Regardless of the yield potential, in the linear part of the curve, the balanced N, P and K removal by 1000 kg grain were 18.3, 3.6 and 3.5 kg, respectively, and the N:P:K ratio in the grain was 5.08:1:0.97. Compared to balanced nutrient uptake in total above-ground plant, approximately 80%, 82% and 18% of N, P and K accumulated in grain and were removed from the field. These values should provide practical algorithms for fertilizer recommendation to sustain soil fertility.

3.4. Evaluation of the relationship between yield and nutrient uptake

The datasets in each envelope were from the field experiments conducted from 2000 to 2011 dealing with N, P and K treatments in China. The yield potential (defined as maximum yield) (Liu et al., 2011b; Setiyono et al., 2011) was set at 12,000 kg/ha, 10,000 and 11,000 kg/ha in North Central China, the middle and lower reaches of the Yangtze River and Northwest China,

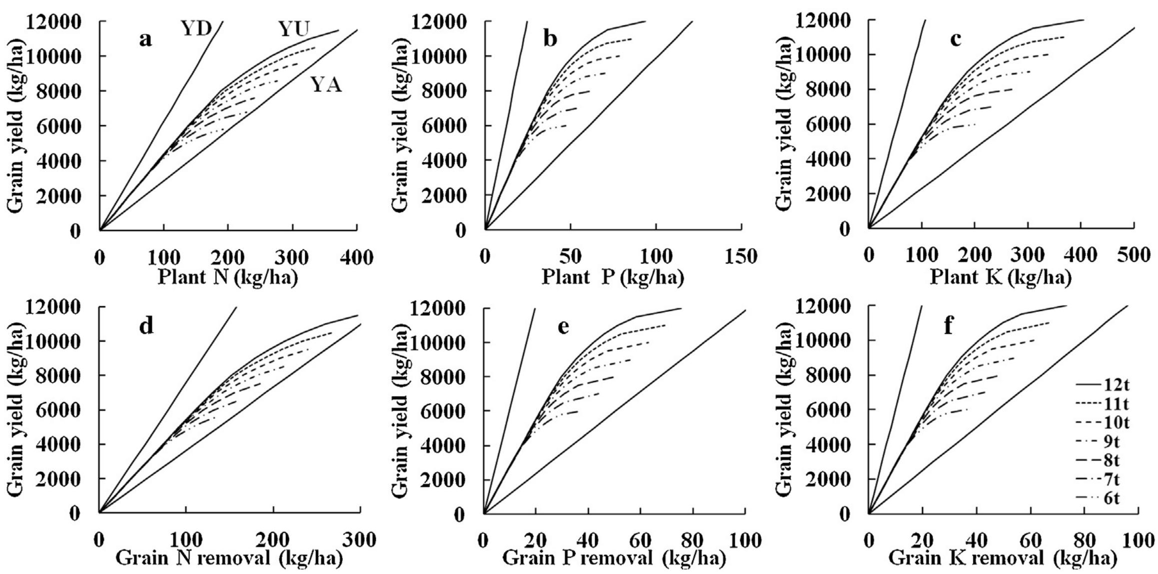

Fig. 3. Balanced nutrient requirement (a–c) and grain nutrient removal (d–f) for N, P and K under different yield potentials simulated by the QUEFTS model. YD, YA and YU are the maximum dilution, maximum accumulation and balanced uptake of N, P and K in above-ground plant dry matter or in the grain nutrient removal, respectively, which are calculated by the QUEFTS model from excluding the upper and lower 2.5 percentiles of all internal efficiency data (HI ≥ 0.40).

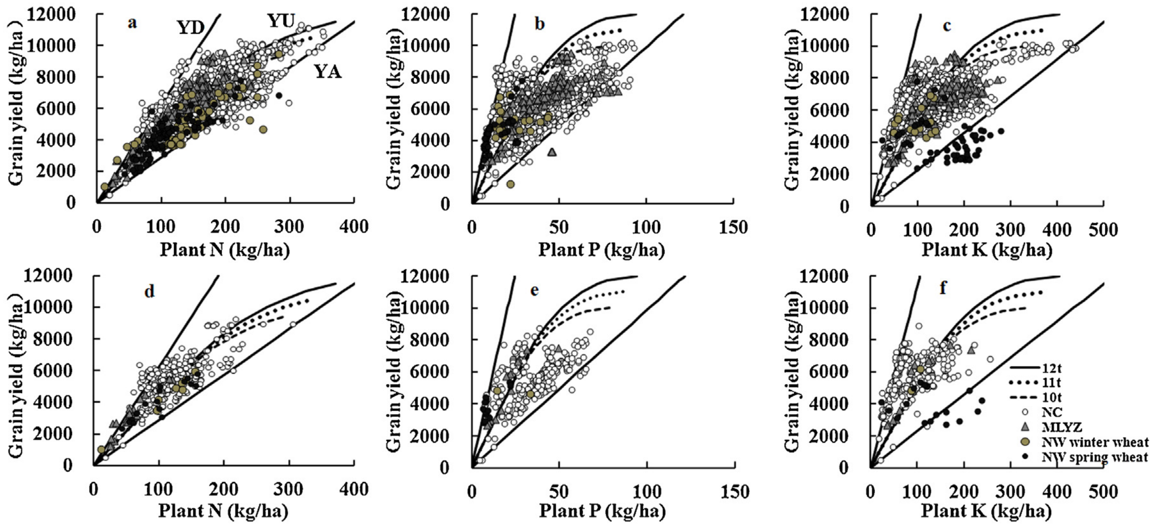

Fig. 4. Relationship between grain yield and N, P and K uptake in North Central China (NC), the middle and lower reaches of the Yangtze River (MLYR) and Northwest China (NW). The yield potential was set at 12,000, 10,000 and 11,000 kg/ha in NC, MLYR and NW, respectively. Fig. 4(a–c) were datasets from all experiments of China, and Fig. 4(e–f) were datasets from CK (unfertilized plots) and N, P or K omission plots. YD, YA and YU are the maximum dilution, maximum accumulation and balanced uptake of N, P and K in above-ground plant dry matter, respectively, which are calculated by the QUEFTS model from excluding the upper and lower 2.5 percentiles of all internal efficiency data (HI ≥ 0.40).

respectively (Fig. 4). If the dataset was above the balanced nutrient uptake line (the linear–parabolic–plateau curve) and close to the upper boundary, it meant the nutrient was deficient supply. In contrast, if the dataset was below the balanced nutrient uptake line and close to the lower boundary, it meant the nutrient was excessive supply and the yield was limited by growth factors other than this nutrient concerned. In North Central China, most N uptake was luxury, while in the middle and lower reaches of the Yangtze River, N uptake was neither luxury nor deficient, meaning that N application in this region was more rational. In Northwest China, more N uptake was excessive both in winter and spring wheat, reflecting that N fertilizer application was excessive, and should be reduced for both economic and environmental purposes (Fig. 4a).

Phosphorus accumulation in winter wheat plant showed both deficiency and luxury in North Central China, indicating that P fertilizer application was not in balance, and that it was not applied according to the soil indigenous P supply and plant demand. Some P uptake in the middle and lower reaches of the Yangtze River showed a trend to excess and in Northwest China, most spring wheat showed deficiency. The P was mainly applied as calcium superphosphate fertilizer or calcium magnesium phosphate fertilizer, or added with N or K fertilizer. For example, compound fertilizers with a N:P:K ratio of 15:15:15 used very frequently would all include more P nutrient than required for the optimum ratio. Phosphorus application should be calculated more carefully, considering soil supply and crop demand to avoid these excesses and deficiencies (Fig. 4b).

Some K uptake showed deficiency in North Central China, and only a few data sets showed luxury. However, spring wheat in Northwest China showed excessive K uptake, very unlike winter wheat (Fig. 4c). The difference may due to the environment where spring wheat was grown. The soil in Northwest China contained much K, which would result in K luxury uptake (Table 2).

Observations from unfertilized plots and N, P and K omission plots were shown in Fig. 4(d–f). Many observations were concentrated near the upper boundary line for high IEs values, reflecting severe nutrient deficiency. There were also some N accumulation data sets and more P accumulation data sets close to the lower boundary lines suggesting that there may be substantial available residual N and P in the soil leading to N and P luxury uptake from an unbalanced nutrient supply.

3.5. QUEFTS model validation

Multiple sites of the OPT plots for wheat in Hebei, Henan, Shandong and Shanxi provinces were conducted in 2010–2011 to validate the QUEFTS model. The NE for wheat decision support system was used to recommend fertilizer application based on the QUEFTS model and SSNM practices through the whole growth

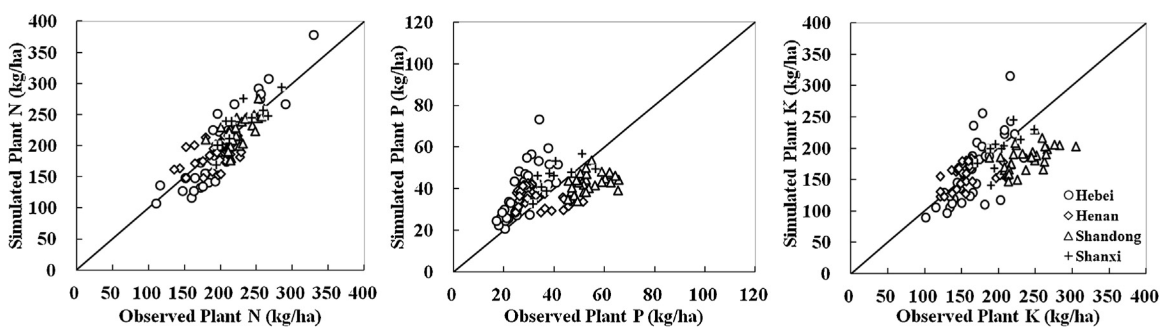

Fig. 5. Relationship between observed and simulated N, P and K uptake in above-ground plant dry matter for wheat. The average application rates of N, P and K were 135, 23 and 50 kg/ha for Hebei; 150, 32 and 62 kg/ha for Henan; 140, 34 and 58 kg/ha for Shandong; and 137, 29 and 65 kg/ha for Shanxi province, respectively.

period. The results showed that the RMSE values were 22.7, 22.4 and 93.0 for N, P and K, respectively, and the *n*-RMSE values were 10.9%, 56.9% and 47.9% for N, P and K, respectively, indicating that the P and K had a larger deviation. However, for all experiments, the observed N, P and K uptake in the above-ground plant dry matter were scattered more or less equally around the 1:1 line, suggesting that the measured values agreed well with the simulated nutrient uptake and there were no significant deviation between each other (Fig. 5), similar to the results of Liu et al. (2006) and Das et al. (2009). It confirmed that the QUEFTS model could be used to calibrate the predicted nutrient uptake and to improve fertilizer recommendations.

4. Conclusions

Based on many grain yield and nutrient uptake datasets collected from 2000 to 2011, a large range of IEs for wheat were observed. When excluded the upper and lower 2.5 percentiles of all IEs data, considering only datasets with HI $\geq$ 0.40, the QUEFTS model described the minimum and maximum internal efficiencies of N, P and K were 28.8 and 62.6 kg grain per kg N, 98.9 and 487.4 kg grain per kg P, and 23.0 and 112.9 kg grain per kg K, respectively. The model predicted a linear increase in yield if nutrients were taken up in balanced amounts of 22.8 kg N, 4.4 kg P and 19.0 kg K per 1000 kg of grain until yield reached about 60–70% of the yield potential, with a N:P:K ratio of 5.18:1:4.32. The corresponding IEs were 43.9 kg grain/kg N, 227.0 kg grain/kg P and 52.7 kg grain/kg K for balanced nutrition. The optimal N, P and K removals in 1000 kg of grain were 18.3, 3.6 and 3.5 kg, respectively, with a N:P:K ratio of 5.08:1:0.97. Compared with balanced nutrient uptake in total above-ground plant, approximately 80%, 82% and 18% of the N, P and K were presented in the grain and removed from the field.

Relationship between grain yield and nutrient uptake could be estimated for wheat in China. The results showed that most N uptake was luxury, P accumulation had both deficiency and excess, and some K uptake showed deficiency. The functions reflected the status of fertilizer application in China and served further as a tool to recommend reasonable fertilization.

Results from field validation of the QUEFTS model in four different provinces, showed a good agreement (Normalized RMSE = 10.9%, 56.9% and 47.9% for N, P and K, respectively) between observed and simulated nutrient uptake in above-ground plant. The QUEFTS model could be used as a database to support the NE for Wheat system and to recommend balanced fertilizer practices for farmers. As a result, these would help to optimize crop yield and avoid nutrient depletion or excess application, and also could improve nutrient use efficiency, economic benefits and environment sustainability.

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Establishing a scientific basis for fertilizer recommendations for wheat in China: Yield response and agronomic efficiency

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ABSTRACT

The inappropriate application of fertilizer has become a common phenomenon in wheat production systems in China and has led to nutrient imbalances, inefficient use and large losses to the environment. However, defining an appropriate fertilization rate remains the foundation to science-based nutrient management. This paper described a new fertilizer recommendation method for wheat in China based on yield response and agronomic efficiency using datasets from 2000 to 2011. The results showed that the mean yield responses of wheat to N, P and K were 1.7, 1.0 and 0.8 t/ha, respectively. Nitrogen was the nutrient most limiting yield, followed by P and then K. The soil indigenous nutrient supplies were 122.6 kg N/ha, 38.0 kg P/ha, and 120.2 kg K/ha. The mean agronomic efficiencies were 9.4, 10.2 and 6.5 kg/kg for N, P and K, respectively. There was a significant negative exponential relationship between yield response and indigenous nutrient supply, and a significant negative linear correlation between yield response and relative yield. It was also demonstrated a quadratic equation between yield response (x) and agronomic efficiency (y) ($P < 0.05$). The relationship between yield response (x) and agronomic efficiency (y) for N was $y_N = 0.3729x_N^2 + 6.1333x_N + 0.1438$ ($R^2 = 0.76$, $n = 601$), for P was $y_P = 0.5013x_P^2 + 8.3209x_P + 2.3907$ ($R^2 = 0.65$, $n = 288$), and for K was $y_K = 1.6581x_K^2 + 9.099x_K + 0.7668$ ($R^2 = 0.58$, $n = 379$). These equations were all incorporated as part of the *Nutrient Expert for Wheat* fertilizer recommendation decision support system. The results of multiple field experiments helped to validate the feasibility of the recommendation model and concluded that *Nutrient Expert for Wheat* could be used as an alternative method to make fertilizer recommendations in China.

1. Introduction

Wheat (*Triticum aestivum* L.) is one of the important cereal crops in China, and fertilizer applications have played a major role in increasing yield. However, in the pursuit of meeting food security in China, over-application of N fertilizer has been a common practice in wheat production systems and has led to nutrient imbalances, inefficient fertilizer use and large losses to the environment (Cui et al., 2008a; Ju et al., 2009). Having access to a science-based fertilizer recommendation is critical for improvement of fertilizer use efficiency in high yielding crops. However, how to establish fertilizer recommendations suitable for smallholder farming households in China remains a challenge.

Soil testing method has been developed as a means of improving fertilizer use efficiency in China. He et al. (2009) did multiple-point field experiments based on soil testing in North Central China and showed that soil test based fertilizer recommendations could increase wheat and maize yield and improve fertilizer use efficiency. However, there are challenges associated with soil testing, including taking representative soil samples, identifying an analytical method suitable for the location soils, and establishing a method which predicts soil nutrient supply capacity. Additionally, soil testing is time-consuming and expensive. In smallholder farming households, the main management units in China, soil testing is viewed as a very expensive tool, and the time required to get results are often not feasible in multiple cropping situations. Even if soil test values are suitable, there still remains the challenge of selecting a science-based fertilizer recommendation philosophy (Hou et al., 2002; He et al., 2012).

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Nutrients for plant uptake come from both external inputs such as fertilizer and manure, but also the soil itself. In ^{15}N-labeled micro-plot experiments of wheat, Ju et al. (2002) showed that there was 45% of the total nitrogen uptake coming from the fertilizer, and 55% from the soil. Soil nutrient mineralization is often used as a means of assessing soil indigenous nutrient supply in an unfertilized crop. Results showed that when N fertilizer was applied at 120 and 360 kg N/ha for wheat, the soil mineralized nitrogen was 78.6 and 58.1 kg N/ha, representing 65.5% and 16.1% of fertilizer N application, respectively. The lower N application promoted mineralization, making it the majority supply for crop growth (Ju et al., 2002). Experiments in North Central China showed that the nitrogen input by atmospheric deposition for one year was 80–90 kg N/ha, another important source for crop nutrients (Liu et al., 2006b; He et al., 2007; Zhang et al., 2008b). Irrigation water in China often has high levels of N, P, K and trace elements, supporting crop yields and maintaining soil fertility. The mean nitrogen input from irrigation water in the winter wheat–summer maize cropping system in North Central China was 13 kg N/ha (Chen and Zhang, 2006). Biological nitrogen fixation provides another N source in agricultural ecosystem. Lu (1998) pointed out that biological nitrogen fixation was 30 kg N/ha on rice, and Zhu (1992) showed that non-symbiotic nitrogen fixation was 15 kg N/ha in wheat and maize in arid production regions. Sometimes soil test values do not reflect soil nutrient supply capacity. Research showed that P supplied from the soil was always higher than determined by soil test extraction, attributed to root exudation dissolving some unavailable P and large root systems capable of absorbing P from deeper soil (Gransee and Merbach, 2000). It was generally agreed that the available nutrients extracted from the soils by chemical methods provided only a relative value (Tang, 1994; Weigel et al., 2000). Those nutrients coming from the environment and soil, all of which influence fertilizer use efficiency, are called the soil indigenous nutrient supply. The yields in fertilized plots are composed of two parts, one is the yield from the soil indigenous nutrient supply, and the other is from fertilizer application. Making fertilizer recommendations based on soil indigenous nutrient supply has the potential to help reduce the application rates and fertilizer losses, and to improve fertilizer use efficiency.

The *Nutrient Expert for Wheat* is a decision support system being developed by the International Plant Nutrition Institute (IPNI), with the goal of supporting advisors who make fertilizer recommendations to farmers (Pampolino et al., 2012). The *Nutrient Expert for Wheat* system uses site-specific nutrient management (SSNM) principles, which include the use of the Quantitative Evaluation of the Fertility of Tropical Soils (QUEFTS) model to determine crop nutrient uptake requirements. SSNM was initially used for rice in the mid-1990s as an alternative approach for dynamic management of nutrients, and to optimize supply and demand of a nutrient within a specific field in a particular cropping season (Dobermann et al., 2002). The QUEFTS model was originally developed by Janssen et al. (1990) and was transformed and validated to estimate the optimum nutrient requirement at a target yield (Smaling and Janssen, 1993; Witt et al., 1999, 2008; Pathak et al., 2003; Liu et al., 2006a; Buresh et al., 2010; Setiyono et al., 2010; Chuan et al., 2012).

The core of the fertilizer recommendation method in *Nutrient Expert for Wheat* is based on yield response and agronomic efficiency (AE). The yield response to N, P or K is the yield gap between NPK plots that received ample nutrients and omission plots when one of the nutrients is omitted. The agronomic efficiency of N, P or K (AEN, AEP or AEK) is the yield increase per unit of fertilizer N, P_2O_5 or K_2O applied. Fertilizer recommendation based on yield response and agronomic efficiency is an alternative approach developed for use when soil testing is not available, also considers the N, P and K interactions, and this is an unique feature

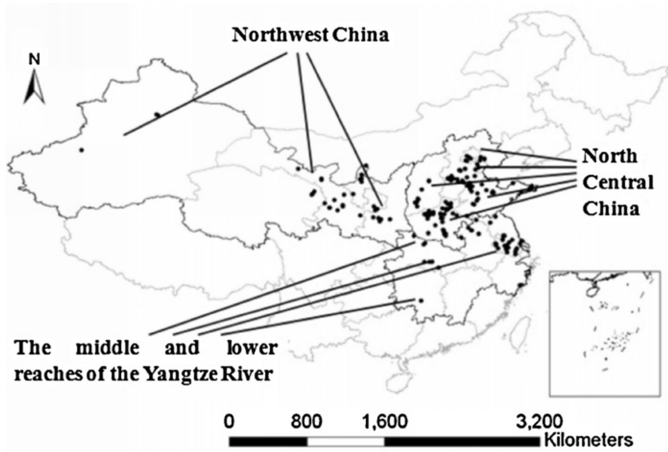

Fig. 1. Geographical distribution of studied locations in North Central China, the middle and lower reaches of the Yangtze River, and Northwest China.

compared with other decision support systems. The determination of fertilizer N requirements from *Nutrient Expert* has been modified to use a target agronomic efficiency and an estimation of yield response to applied N (Buresh and Witt, 2007; Witt et al., 2007; Pampolino et al., 2011). The determination of fertilizer P and K requirements considers the internal nutrient efficiency combined with estimates of attainable yield, nutrient balances, and yield responses from added nutrient within specific fields (Witt et al., 2007; Pampolino et al., 2011). This method utilizes soil indigenous nutrient supply in an attempt to avoid excessive nutrient accumulation in the soil and has been applied with success in rice, maize and wheat crops in some Asian countries (Witt et al., 2007; Buresh et al., 2010; Pampolino et al., 2011; Satyanarayana et al., 2011).

Previously there was no systematic analysis of yield response and agronomic efficiency data across multiple-site and multiple-year from the wheat production areas of China. The objectives of this paper were: (1) to determine yield response, agronomic efficiency and soil indigenous nutrient supply in the main wheat production areas in China; (2) to analyze the inter-relationships among yield response, agronomic efficiency, and soil indigenous nutrient supply; and (3) to develop principles and a scientific basis for fertilizer recommendations using the *Nutrient Expert for Wheat* decision support system.

2. Materials and methods

2.1. Data source

Datasets for grain yield, fertilizer applications, and N, P and K uptake in mature above-ground plant dry matter were compiled from published literature from 2000 to 2011 in China, along with published and unpublished datasets from the International Plant Nutrition Institute (IPNI)-China Program database. The datasets contained different nutrient management practices including farmers' practice (FP), optimum practice treatment (OPT), long-term field experiments and treatments with different fertilizer rates across wheat-growing environments of China, encompassing North Central (NC), the middle and lower reaches of the Yangtze River (MLYR) and Northwest China (NW) (Fig. 1). The data included a wide range of soil types and climatic conditions (Table 1). The varieties in the experiments were all commonly used in local high yield production and highly represent the great variation in wheat production.

Table 1
Climate characters of experimental sites for wheat production in three regions of China.

Region	Province	Season	n[a]	Precipitation (mm)	Latitude	Longitude	T_{min} [b]	T_{max} [c]
NC[d]	Hebei	Winter	1305	350–500	38.04	114.51	−8	33
	Henan	Winter	2009	500–900	34.75	113.62	−3	33
	Shanxi	Winter	856	350–700	36.09	111.52	−4	28
	Shandong	Winter	1161	550–950	36.67	116.99	−3	30
	Beijing	Winter	62	550–650	39.90	116.41	−10	33
MLYR[e]	Jiangsu	Winter	616	800–1200	32.06	118.80	3	30
	Hubei	Winter	160	750–1500	30.59	114.31	−4	35
	Anhui	Winter	151	750–1700	31.82	117.23	−1	30
	Hunan	Winter	11	1200–1750	28.23	112.94	4	35
NW[f]	Shaanxi	Winter	312	350–650	34.26	108.94	−10	28
	Ningxia	Spring	232	200–600	38.47	106.26	−9	25
	Gansu	Spring	599	100–300	36.06	103.83	−19	36
	Xinjiang	Winter	11	100–300	43.79	87.63	−20	33

[a] n = the number of the observations.
[b] T_{min} = minimum temperature.
[c] T_{max} = maximum temperature.
[d] NC = North Central China.
[e] MLYR = the middle and lower reaches of the Yangtze River.
[f] NW = Northwest China.

2.2. Overview for field validation

The multiple sites for the experiments were conducted in farmers' fields in Hebei (32 fields) (115°18′E, 37°47′N), Henan (20 fields) (115°13′E, 35°46′N), Shandong (30 fields) (116°24′E, 37°6′N) and Shanxi (10 fields) (111°18′E, 35°48′N) provinces to validate the feasibility of fertilizer recommendations provided by the *Nutrient Expert for Wheat* decision support system. The four provinces were located in North Central China with a winter wheat/summer maize rotation on the fluvo-aquatic or cinnamon soil. Winter wheat was sown after the harvest of maize at the beginning of October and harvested in mid-June of the following year.

Treatments were arranged using a randomized complete block design, where one-farm represented one-replicate design. The size of each treatment ranged from 30 to 40 m^2. The treatments included a CK (check, no fertilizer applied), a balanced OPT-NE (fertilizer application based on *Nutrient Expert for Wheat* decision support system), a balanced OPT-S (fertilizer application based on soil testing), a FP (fertilizer application based on farmers' traditional practice), and a series of nutrient omission plots, which excluded N, P or K from the OPT-NE treatment. In Hebei province, the application rates in OPT-S were the same as OPT-NE, so only OPT-NE was considered at that location. The fertilizer sources were urea, single superphosphate and potassium chloride. Urea was split applied two (basal and top dressed by broadcasting at the jointing stage) or three times (basal and top dressed at the jointing stage and filling stage) depending on soil fertility or expected yield response to N, while P and K fertilizers were both broadcast and incorporated as basal before seeding. The rates of fertilizer application were listed in Table 2. Irrigation and other cultural practices were applied using the best local management.

At harvest, three 1 m × 1 m from a location in the middle of each plot was harvested manually to determine straw and grain yield. Harvested straw and grain samples were oven-dried at 60 °C for the determination of dry matter weight. Subsamples of straw and grain were collected and analyzed for the determination of N concentration. Details for the analysis and calculation methods of N concentration, total N uptake, AEN, recovery efficiency of N (REN), and gross profit (the gross return above fertilizer cost) were previously described by He et al. (2009). The partial factor productivity of N (PFPN) was calculated as follows:

$$\text{PFPN (kg/kg)} = \frac{\text{grain yield}}{\text{fertilizer N applied}}$$

Data was analyzed using ANOVA with SPSS 13.0 for Windows. Mean separation between different treatments was calculated using least significant difference (LSD) at 0.05 or 0.01 level.

Table 2
Rates of fertilizer application.

Province	Treatment	Fertilizer application (kg/ha)		
		N	P_2O_5	K_2O
Hebei	FP[a]	278 (196–344)[d]	42 (30–68)	24 (0–68)
	OPT-NE[b]	135 (130–150)	52 (50–56)	60 (48–70)
Henan	FP	184 (113–289)	124 (72–225)	127 (27–225)
	OPT-S[c]	210	90	120
	OPT-NE	144 (140–155)	67	70 (60–80)
Shandong	FP	317 (215–400)	161 (75–276)	13 (0–36)
	OPT-S	242	150	60
	OPT-NE	140	78	70 (60–80)
Shanxi	FP	262 (179–502)	110 (19–194)	28 (14–72)
	OPT-S	180	75 (67–90)	76 (60–80)
	OPT-NE	137 (125–140)	67	78 (60–80)

[a] FP = fertilizer application based on farmers' traditional practice.
[b] OPT-NE = fertilizer application based on *Nutrient Expert for Wheat* decision support system.
[c] OPT-S = fertilizer application based on soil testing.
[d] Data in parentheses indicates the range of fertilizer application.

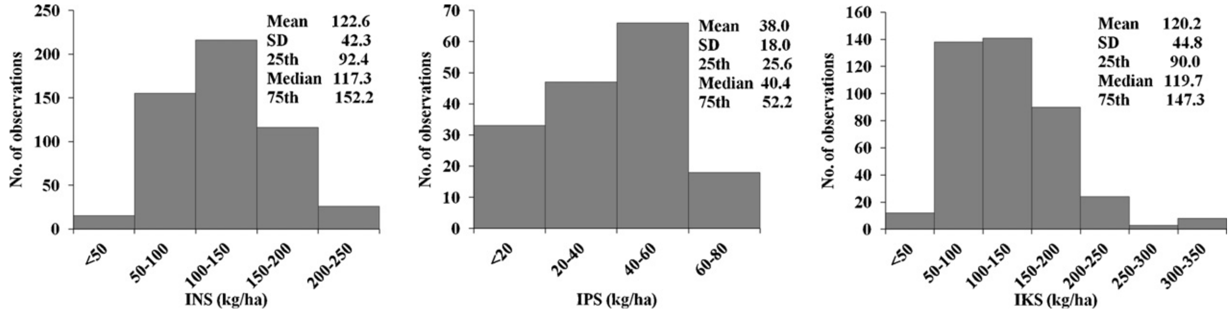

Fig. 2. Frequency distribution of indigenous nutrient supply of N, P and K for wheat. The INS, IPS and IKS mean indigenous N, P and K supply, respectively.

3. Results and discussion

3.1. Indigenous nutrient supply

Indigenous nutrient supply was defined as the total amount of a particular nutrient uptake in the omission plots (Janssen et al., 1990). For a specific field, indigenous nutrient supply was an indicator of soil fertility and could be used to estimate fertilizer recommendations for site-specific nutrient management (Dobermann and Cassman, 2002; Dobermann et al., 2003; Cui et al., 2008b). The frequency distribution of indigenous nutrient supply of N, P and K was shown in Fig. 2. There were 40.9% of the observations of indigenous N supply (INS) between 100 and 150 kg N/ha for wheat season. There were 68.9% and 67.1% of the observations of indigenous P supply (IPS) and indigenous K supply (IKS) between 20 and 60 kg P/ha and 50 and 150 kg K/ha, respectively. On average the mean indigenous nutrient supplies for wheat were 122.6 kg N/ha, 38.0 kg P/ha, and 120.2 kg K/ha. These results indicated that the indigenous nutrient supply was relatively high and should be considered when making fertilizer recommendations focused on achieving the optimal nutrient management. The values of INS, IPS and IKS in the wheat season in China were much higher than those determined for Punjab State in Northwest India (i.e., INS 66.3, IPS 15.5 and IKS 79.1 kg/ha) and in Northeast Thailand (i.e., INS 38, IPS 10 and IKS 89 kg/ha) (Naklang et al., 2006; Khurana et al., 2008). Liu et al. (2006a) using the data from 1985 to 1995 in China concluded that the indigenous nutrient supplies for wheat were 54.1 kg N/ha (n = 345), 14.2 kg P/ha (n = 74) and 93.4 kg K/ha (n = 91), respectively. The values in the current study were much higher than previously determined, reflecting over-application of fertilizers in many regions of China, also increasing both residual nutrients and the potential for losses into the environment.

3.2. Yield response and relative yield

Under average growing conditions, crops free of biotic or abiotic stress will show a small yield response in the presence of a high nutrient supply, and a large yield response with a low nutrient supply. The frequency distribution of wheat yield responses to N, P and K fertilizer application was shown in Fig. 3. The results showed that about 88% of all the observations had a yield response to N less than 3.0 t/ha. There were 62.8% and 72.7% of the yield responses to P and K, respectively, below 1.0 t/ha. The mean yield response to N was 1.7 t/ha, with a range from 0 to 5.9 t/ha. The yield response to P was 1.0 t/ha (ranged from 0 to 4.0 t/ha), and to K was 0.8 t/ha (ranged from 0 to 4.0 t/ha). Clearly, N fertilizer played a primary role in wheat yield increase in this region.

The N, P or K nutrient-limited yield is that achieved where this individual nutrient is absent while all other nutrients are available in ample amounts. The attainable yield is the yield achieved with ample amounts of all nutrients (N, P and K) referred to here as full NPK, OPT or SSNM. The relative yield (GY0/Ya) is the ratio between nutrient-limited yield and attainable yield, suggesting the soil indigenous nutrient supply capacity. A larger relative yield means higher soil indigenous nutrient supply and represents higher soil fertility, while a lower relative yield means lower soil indigenous nutrient supply and lower soil fertility. The results showed that most of the 'GY0N/Ya' (the ratio between N-limited yield and attainable yield) and 'GY0P/Ya' (the ratio between P-limited yield and attainable yield) were distributed at 0.6–1.0, and most of 'GY0K/Ya' (the ratio between K-limited yield and attainable yield) was between 0.8 and 1.0 (Fig. 4). The mean relative yields for P and K were higher at 0.85 and 0.90, respectively, while relative yield for N was 0.76, indicating that N was the first nutrient limiting factor for yield, followed by P, and then K.

The yield in the full NPK, OPT or SSNM is higher under a 'favorable' environment than under an 'average' or 'poor' condition. Also, under the same climatic condition, the nutrient-limited yield increases as the attainable yield increases. Additionally, the indigenous nutrient supply (or native soil fertility) could determine the nutrient-limited yield and relative yield. The 25th percentile, median, and 75th percentile of all data for the relationship 'GY0/Ya' could be used as coefficients to estimate the nutrient-limited yield for a given attainable yield and soil fertility class. It assumes

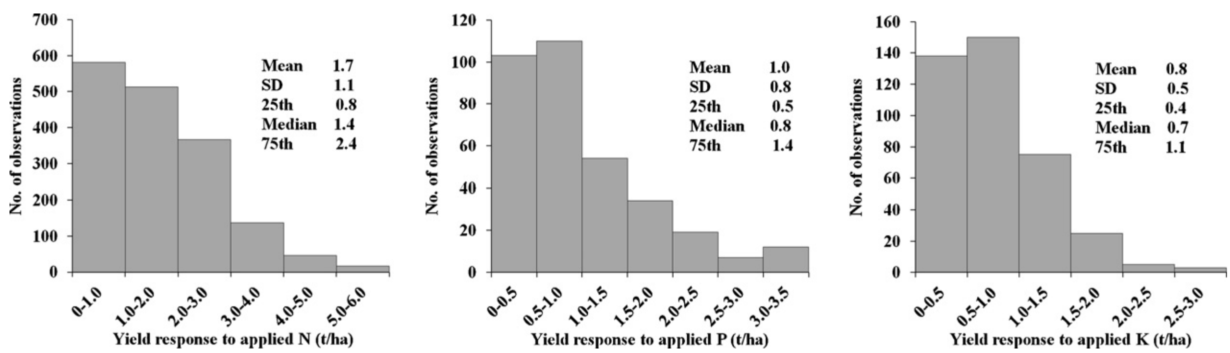

Fig. 3. Frequency distribution of yield responses to applied N, P and K fertilizer for wheat.

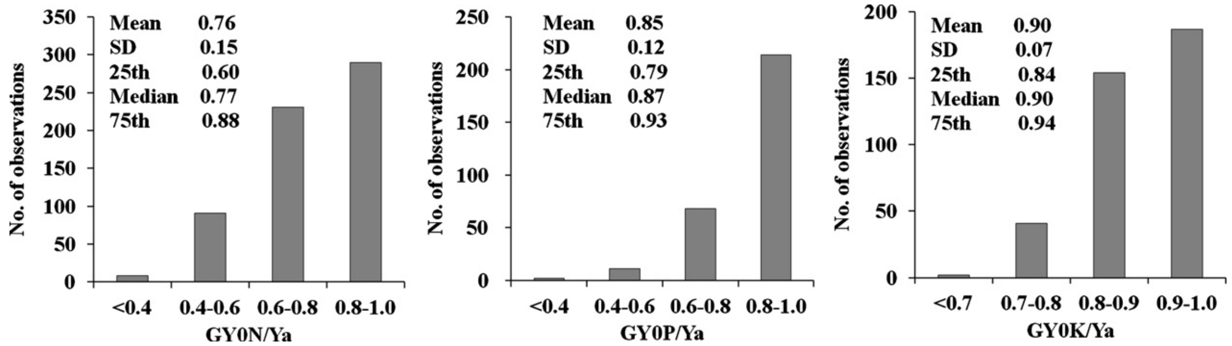

Fig. 4. Frequency distribution of nutrient-limited yield to attainable yield of N, P and K for wheat. The relative yield 'GY0N/Ya', 'GY0P/Ya' and 'GY0K/Ya' are the ratios between N, P and K nutrient-limited yield and attainable yield, respectively.

that the median represents soils with 'average' nutrient supply or fertility class, and the 25th and 75th percentile represent 'low' and 'high' nutrient supply or fertility classes, respectively (Pampolino et al., 2012). Results showed that values for 'GY0N/Ya' were 0.60, 0.77 and 0.88 for low, medium, and high N supply, respectively—corresponding to the 25th percentile, median, and 75th percentile of all data ($n = 620$) from China. The values for 'GY0P/Ya' were 0.79, 0.87 and 0.93 for low, medium, and high P supply, respectively ($n = 295$), and values for 'GY0K/Ya' were 0.84, 0.90 and 0.94 for low, medium, and high K supply, respectively ($n = 406$). For example, when given an attainable yield, combined with these coefficients and soil fertility classes, the nutrient-limited yield for N, P and K could be calculated and yield response to N, P and K then could be estimated.

3.3. Agronomic efficiency

The frequency distribution of agronomic efficiency for wheat was shown in Fig. 5. The mean agronomic efficiencies for N, P and K were 9.4, 10.2, 6.5 kg/kg respectively, indicating that 61.6%, 55.2% and 83.9% of the observations were lower than 10 kg/kg, respectively. Dobermann (2007) reported that AEN for cereals in developing countries ranged between 10 and 30 kg/kg, and also indicated that AEN could reach an average value >25 kg/kg in a well-managed system with low levels of N use or with low soil N supply. However, compared with developed countries, the nutrient use efficiency in China was still only at the baseline reported by Dobermann (2007), and only reached about 52% of the world average (18 kg/kg) reported by Ladha et al. (2005). Agronomic efficiency of N remains low in China, highlighting the need to improve nutrient management practices in modern production systems (Zhao, 1997; Chen, 2003; Cui, 2005; Gao et al., 2008; Zhang et al., 2008a).

3.4. Relationship between yield response and indigenous nutrient supply

The indigenous nutrient supply (y) showed a significant negative exponential relationship with yield response (x) ($P < 0.05$) (Fig. 6) with 36%, 28% and 43% of the variability for N, P and K, respectively. For a specific field site, when the indigenous nutrient supply was high, the yield response to the applied nutrient was low. These results support the approach that the yield responses could be used as an indicator of soil nutrient supplying capacity.

3.5. Relationship between yield response and relative yield

As previously described, when the relative yield (GY0/Ya) is high, the basic soil nutrient supply is high, and the yield response to the applied nutrient is low. Results showed that the coefficients between yield response and relative yield were 0.93 ($R^2 = 0.87$) for N, 0.90 ($R^2 = 0.80$) for P and 0.94 ($R^2 = 0.88$) ($P < 0.05$) for K. The relative yield gradually decreased as the yield response increased, and there was an extremely significant negative linear correlation between yield response (x) and relative yield (y) ($P < 0.01$) (Fig. 7).

3.6. Relationship between yield response and agronomic efficiency

The yield in an unfertilized plot is mainly supported by the soil indigenous nutrient supply. The yield response between the yield in an unfertilized plot and the target yield is supplied by fertilizer application. The yield response varies as the soil indigenous nutrient supply changes. The agronomic efficiency is also determined by the indigenous nutrient supply, fertilizer application, management practices and climatic conditions. The results showed that there

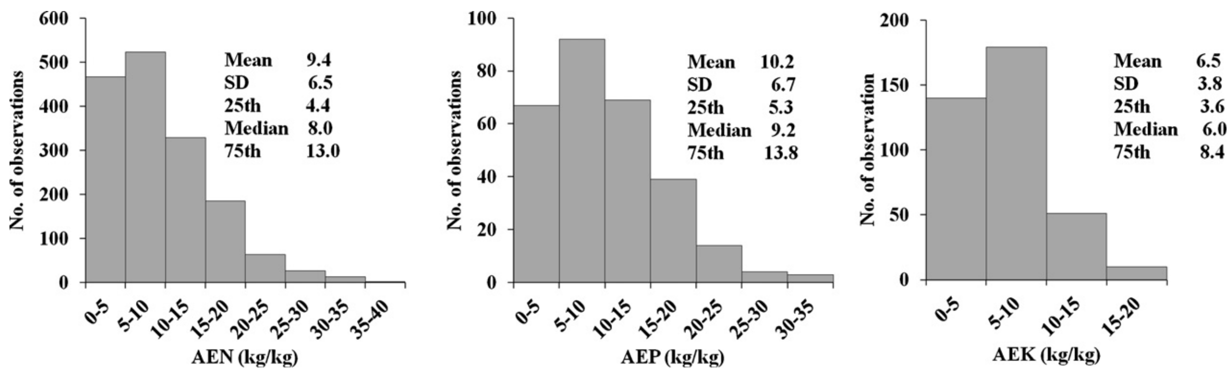

Fig. 5. Frequency distribution of agronomic efficiency of N, P and K for wheat. The AEN, AEP and AEK mean agronomic efficiency of N, P and K, respectively.

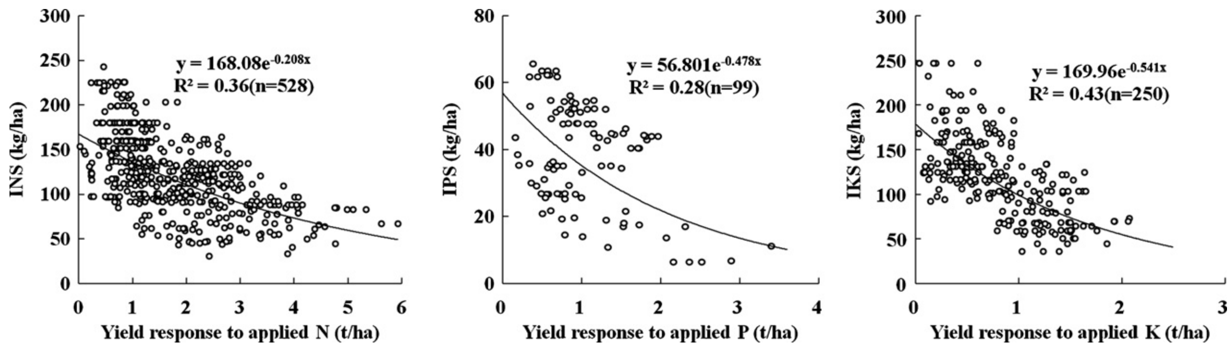

Fig. 6. Relationship between yield response and the indigenous nutrient supply. The INS, IPS and IKS mean indigenous N, P and K supply, respectively.

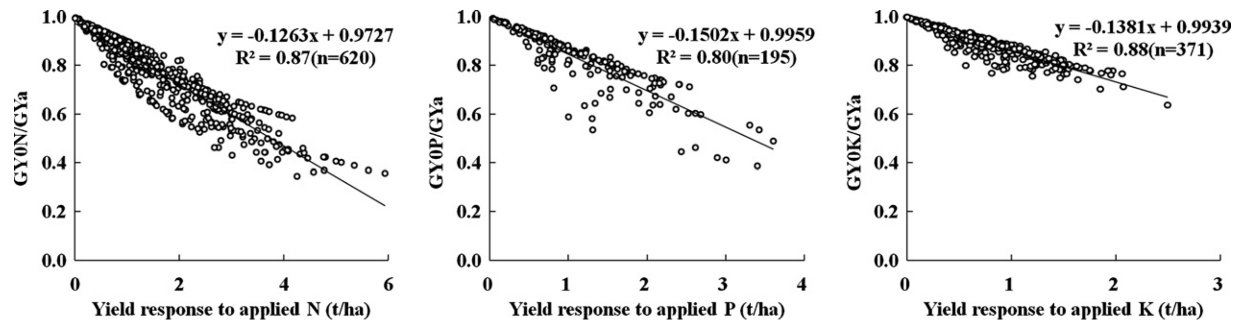

Fig. 7. Relationship between yield response and relative yield for wheat. The relative yield 'GY0N/Ya', 'GY0P/Ya' and 'GY0K/Ya' are the ratios between N, P and K nutrient-limited yield and attainable yield, respectively.

was a significant quadratic relationship between yield response (x) and agronomic efficiency (y) ($P < 0.05$) (Fig. 8).

Relationship for N: $y_N = 0.3729x_N^2 + 6.1333x_N + 0.1438$ ($R^2 = 0.76$, $n = 601$).
Relationship for P: $y_P = 0.5013x_P^2 + 8.3209x_P + 2.3907$ ($R^2 = 0.65$, $n = 288$).
Relationship for K: $y_K = 1.6581x_K^2 + 9.099x_K + 0.7668$ ($R^2 = 0.58$, $n = 379$).

where x_N, x_P and x_K were the yield response to N, P and K, and y_N, y_P and y_K were the agronomic efficiency to N, P and K, respectively.

Initially the agronomic efficiency for a nutrient increased with yield response increasing, but the amount of increase became smaller as the yield response became larger. A lower yield response indicates higher soil indigenous nutrient supply or higher soil fertility, resulting in lower agronomic efficiency. In contrast, a larger yield response means lower soil nutrient supply and relatively higher agronomic efficiency.

3.7. Principles of fertilizer recommendation and field validation

Based on the above analysis, the principles of nutrient recommendations were formed and were incorporated as part of the *Nutrient Expert for Wheat* decision support system (Chuan et al., 2012; He et al., 2012; Pampolino et al., 2012). Nitrogen fertilizer recommendations were calculated from yield response divided by agronomic efficiency. For P and K, both the nutrient from yield gain and maintenance of soil fertility were considered. The nutrient requirements for yield gain were calculated from the yield response and agronomic efficiency, and the maintenance of soil fertility was calculated from the nutrient removal estimated by QUEFTS model (Chuan et al., 2012). Trace elements (such as Zn, Fe, Mn and Mg) were applied if a soil test was showing a deficiency. Multiple points (total 92 fields) of field validation were conducted across North Central China in Hebei, Henan, Shandong and Shanxi provinces in 2010–2011, respectively, to test the feasibility of *Nutrient Expert* decision support system. The OPT-NE plots increased grain yield by 3.7%, 0.1% and 1.1% compared with that in FP plots in Hebei, Henan and Shandong provinces. This occurred with a net reduction

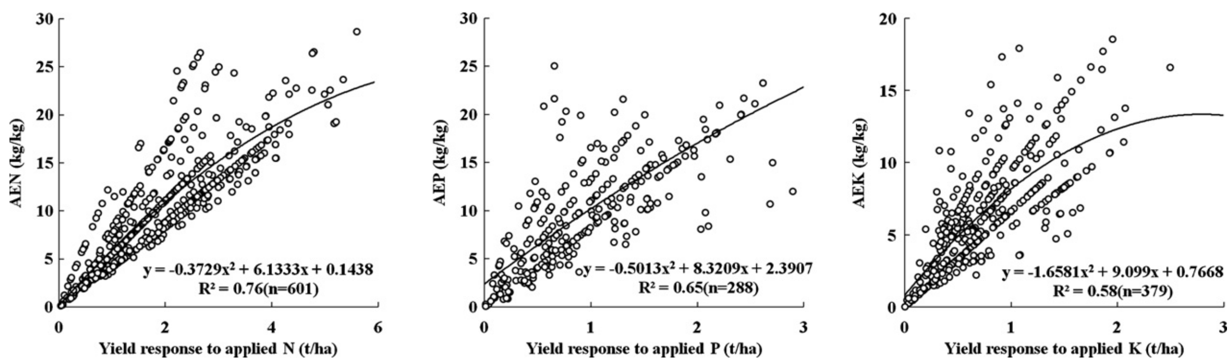

Fig. 8. Relationship between yield response and agronomic efficiency for wheat. The AEN, AEP and AEK mean agronomic efficiency of N, P and K, respectively.

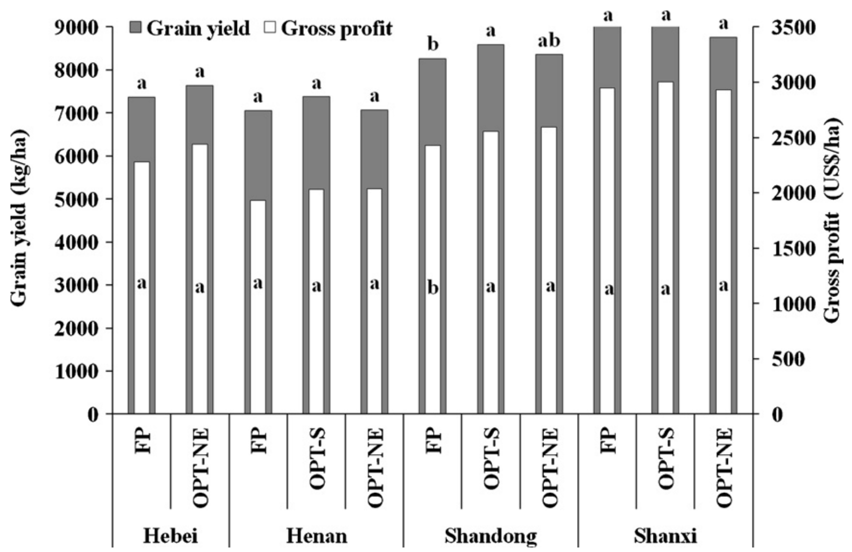

Fig. 9. The grain yield and gross profit in Hebei, Henan, Shandong and Shanxi provinces in 2010–2011. The fertilizer rates in OPT-NE, OPT-S and FP were based on *Nutrient Expert for Wheat* decision support system, soil testing and farmers' traditional practice, respectively. The gross profit was the gross return above fertilizer cost. The prices of wheat in Hebei, Henan, Shandong and Shanxi were 2.2, 2.0, 2.12 and 2.3 RMB/kg, respectively; Prices for N, P_2O_5 and K_2O were 5.0, 6.3 and 7.3 RMB/kg in Hebei, 4.0, 5.6 and 5.0 RMB/kg in Henan, 4.4, 4.8 and 5.3 RMB/kg in Shandong, 5.0, 6.3 and 7.3 RMB/kg in Shanxi province, respectively. 1 US$ = 6.3 RMB. Different letters above the columns mean significant difference ($P < 0.05$).

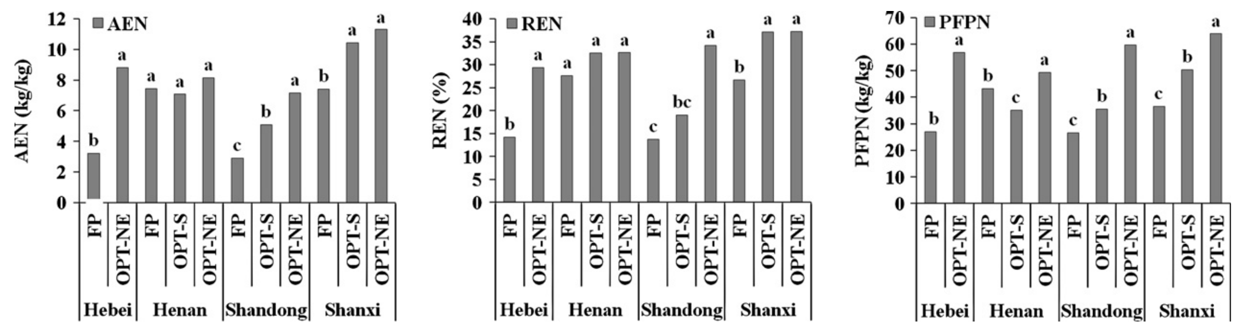

Fig. 10. The agronomic efficiency of N (AEN), recovery efficiency of N (REN) and partial factor productivity of N (PFPN) in Hebei, Henan, Shandong and Shanxi provinces in 2010–2011. Different letters above the columns mean significant difference ($P < 0.05$).

in fertilizer N application in Hebei by 51.4%, Henan by 21.7% and Shandong by 55.8%, and gross profit improvement for the three provinces of 158, 103 and 168 US$/ha, respectively (Fig. 9). However, in Shanxi province, with N and P fertilizer application reduced by 47.7% and 39.1%, it slightly decreased the yield ($P > 0.05$) while maintaining the gross profit. Compared to OPT-S, the yield in OPT-NE was slightly lower, but the gross profit was not significantly decreased ($P > 0.05$) or even improved. The AEN and REN in Hebei, Shandong and Shanxi were significantly enhanced, respectively ($P < 0.05$) (Fig. 10). The averaged AEN in FP ranged from 2.9 to 7.4 kg/kg, and in OPT-NE ranged from 7.2 to 11.3 kg/kg, which were 1.1–2.8 times of FP. The REN in OPT-NE was improved by 5.0–20.5 percentage points compared to FP. The PFPN was significantly improved in OPT-NE. Compared to OPT-S, the AEN, REN and PFPN in OPT-NE were significantly increased in most sites ($P < 0.05$).

4. Conclusions

Based on the data from the literature over the years 2000–2011, it was found that the mean yield responses of wheat to N, P and K were 1.7, 1.0 and 0.8 t/ha in China, respectively. Nitrogen was the nutrient most limiting yield, followed by P and then K. The indigenous nutrient supplies for wheat were 122.6 kg N/ha, 38.0 kg P/ha, and 120.2 kg K/ha. The mean agronomic efficiencies were 9.4, 10.2 and 6.5 kg/kg for N, P and K, respectively.

In this study we determined that there was a significant negative exponential relationship between yield response and soil indigenous nutrient supply ($P < 0.05$), and a significant negative linear correlation between yield response and relative yield ($P < 0.05$). We also demonstrated a quadratic equation between yield response (x) and agronomic efficiency (y) ($P < 0.05$). Based on the above analysis, the principles of nutrient recommendations were formed and incorporated as part of the *Nutrient Expert for Wheat* decision support system. Field validation based on yield response and agronomic efficiency showed a trend to increase both grain yield and gross profit, and AEN, REN and PFPN were all improved in most sites. It was concluded that *Nutrient Expert for Wheat* could be used as an alternative method of soil testing when making fertilizer recommendation.

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