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Table S1 Factors forGHG emissions from fertilizer and pesticide production and transportation, and energy use for irrigation and soil tillage, derived from the footnoted reference(s) for each factor.

Input	unit	GHG emissions (kg CO_2eqper unit input)			
		CO_2	CH_4	N_2O	Total
N fertilizer production[1]	kg N	7.61	0.56	0.03	8.21
P fertilizer production[2]	kg P_2O_5	0.71	0.02	0.00	0.73
K fertilizer production[2]	kg K_2O	0.48	0.02	0.00	0.50
N fertilizer transportation[3-7]	kg N	0.08	0.00	0.00	0.09
P fertilizer transportation[3-7]	kg P_2O_5	0.05	0.00	0.00	0.06
K fertilizer transportation[3-7]	kg K_2O	0.04	0.00	0.00	0.05
Pesticides production and transportation[8]	kg	18.28	0.80	0.05	19.12
Electricity for irrigation[4]	kWh	-	-	-	1.14
Diesel fuel[4-6]	kg	3.38	0.01	0.36	3.75

Supplementary Discussion –Increasing yield and reducing N input

How can weincrease crop yield significantly in the future? Which approaches will be available? Our results show that within our Integrated Soil-crop System Management (ISSM) (described in the main text)only relatively small increases in harvest index (HI) are possible;the average maximum HI for rice, wheat and maize are 0.54, 0.49 and 0.52, respectively.The large yield increases we were able to obtain from increasedbiomass in current cultivars (Extended Data Table 2). This results is in agreementwith previous reports by crop breeders and as well as agronomists[9-12].

Increasing cropbiomass requires designing crop canopiesto make maximum useof solar radiation and periods with favorable temperatures.However, the critical period for increasing biomass varies among the three crops. Our results show that high-yielding maize accumulates substantialbiomass after anthesis[13]but wheat biomass increasesmainly during shooting to anthesis[14], while rice increases biomassboth from tillering to anthesis, and after anthesis[15]. These patterns require management measures thatvaryamong the three crops.

For maize, besides increasing plant density to increase total biomass, it is important to designanappropriate combination of hybrid (growing degree day, GDD) and sowing date according to localresources of solar radiation and temperature, in order to lengthen the growth period after anthesis and therefore increase the accumulation of biomass after anthesis. For tiller crops such as rice and wheat, theappropriate combination of cultivar anddate and amount of sowing (wheat) or transplanting (rice) (depending on local solar and radiation and temperature) establishes afavorabledynamic structure of population and canopy; additionally, topdressing N fertilizer and irrigation (for irrigated wheat) during stem elongationis important to regulate crop population and canopy, and to increasethe biomass accumulation from shooting to anthesis, whilefor rice, topdressing N fertilizer during tilleringas well as headingis important to regulated crop population an canopy, and to increase the biomass accumulation from tillering to anthesis and after anthesis.

Nitrogen applications that meet, but do not exceed, crop N requirements are essential for achieving maximum grainyield and minimizing environmental risks, including nitrate-N leaching and gaseous losses. We found that N requirement for per unit grain were quite different (lower) in high-yielding systems compared with current yield levels. For instance, the N requirement per 1 Mg grain yield ($N_{req.}$) for maize and wheat are only 17.4 and 24.3 kgN, respectively, under high yielding conditions - significantly lower (~20%) than N use atcurrent yield levels[16,17].In addition, more N accumulated in plants in the middle-late growing season in our study[14]. This observation differs from some earlier studies that N accumulation in major cereals mainly occurs in the pre-anthesis stage, and that grain yields are largely depend on the translocation of pre-anthesis assimilates and N uptake[18-20].Ourobservations highlight the importance of N management in the middle-late growing season: the post-anthesis stage in maize, the post-elongation stage in wheat, the heading stage for rice. For ISSM, the proportion of N applied during each period was calculated according to a crop N demand curve, with two applications for wheat (before planting and stem elongation stage), three applications for maize (before planting, 6-leaf stage and 10-leaf stage), and also three applications for rice (before planting, tillering and heading stage).

Our results proved that the ISSM is robust and can increase grain yield while optimizing N input and reducing environmental costs significantly. Our farmer survey suggested that ISSM is possible in practice, because we found about 20% and 5% of rice and wheat farmers respectively report yields already close to ISSM yields with similar amounts of N fertilizer(Extended Data Table4). The ISSM will not cost farmer's additional inputs too much (same amounts of seed and N fertilizer, and almost same times of topdressing) and indeed will take significant benefit to farmers (significant increasing yield), however, there is still a long way to implement ISSM to farmers. Firstly, ISSM must carefully integrate crop (crop variety, sowing amount and date,...) and soil (soil tillage, fertilization, irrigation,...) management measures, according to local eco-conditions, therefore need more intensive localized agronomic researches; secondly, transferring this knowledge-riched approach to less educated small-holder farmers, need more investment and support from various public and private organizations.

Supplementary Discussion – Nr response to increasing N rate or N surplus

It is not possible to measure all of the various Nr (reactive nitrogen) losses (NH_3 volatilization, N leaching, N_2O emission)in-situ directly in a broadmulti-site/year experiments; we and others [21,22] must develop a model to calculate Nr losses. Direct N losses and the environmental footprint of N fertilization are often expressed as a function of rates of N fertilizer application or N surplus in such models. Using an extensive and localized database, we establishedanempirical Nr loss model based on N application or N surplus for all three crops in China.

Earlier studies used a variety of methods to calculate Nr losses. For example, the IPCC methodology[5]adopted a linear relationship to estimate direct N lossesbased on the amount of N added to agricultural soils.However, the relationship between agronomic management and N losses depends on more than just the amount of N input.CropsaccumulateN from the soil in their biomass – and when N fertilizer input is less than or closely matches crop requirements, N uptake can consume the N available in the root-zone and thus limit N losses. Excessive soil N levels, which occur when N additions exceed crop requirements, canlead to nitrate accumulation and promote the production of N_2O in soil or N leaching[23-25]. Consistent with this expectation, some recentfield studies have reported exponential increases in direct N_2O emissions and nitrate leachingwith increasing N applicationrates, indicating a larger proportion of N is lost at high N application rates[26-28].

In many cases it is more useful to compare N losses to levels of N surplus rather than N application rates. The IPCC method to estimate N_2O emissions based on a fixedproportion of applied N inputs islikely to overestimate N loses from well-managed, high-yield,and high-input systems[5].

Our results clearly indicated that both IP and ISSM could control the N surplus to around zero (Table 1) thereby substantially decreasing N leaching, N_2O emission and N runoff (Fig. 1). Here, N surplus iscalculated asN fertilizer minus N uptake by crops; itdoesnot account for inputs of N via deposition[29]andirrigation water, and return of harvested straw to fields. TotalenvironmentalNinputs reached about 89 kg Nha^{-1} for rice-wheat system in theTaihu region and about 104 kg N ha^{-1} for wheat-maize system on the North ChinaPlain[30], so N losses can and do persist even when the N surplus is zero. In the longer run, low N surpluses on a regional scale lead to reduced losses via leaching and atmospheric fluxes, and so reduced environmental inputs of N.

Ammonia losses follow a different dynamic that do other Nr losses. Normally NH_3volatilizationoccurswithin 1 to 2 weeks after fertilization[30]. Consequently, the ability ofN uptake by crop roots to acquire NH_3islimited in this short period,resultinga linear response of NH_3 volatilization to the N application rate(Extended Data Figure 2). We found that NH_3volatilization in agricultural systems in China is quite high (Fig 1), partly because calcareous soils with high pH are widespread in China, partly because mostN fertilizers used in China are easily volatilized urea and ammonia bicarbonate[1].NH_3volatilization represents a large loss from cropping systems. It also represents a significant threat to human health as well as the environment; NH_3in the atmosphere reacts with other air pollutants to create smalland dangerous aerosol particles (PM2.5) that canlodge deep in the lungs, causing asthma attacks, bronchitis, and heart attacks[31,32]. Mitigating NH_3volatilization from agriculture should focus on agronomic measures such as application method (deep application into the soil) as well as developing and adopting new fertilizers such as slow/controlled release coated fertilizer and urease inhibitors[33].

Althoughwe collected as complete and as large a database of N losses as possible, uncertaintyin the magnitude ofN losses still persists. The primary limitation to compiling a larger data set for this analysis was the absence of yield data in studies where GHG (or Nr losses) was measured. In this study, included all data sources from Chinesejournals (or thesis) and ISI journals that met our criteria;we found the data from these two groups coincide well (Extended Data Figure 2-4). In addition to N surplus (or N application rate for NH_3), N losses also depend on specific local conditions and other management practices; together these include topography, soil type, climate, N application method, and N fertilizer type [34-36]. Where possible, these environmental factors and crop practices affecting Nr losses should be taken into account in calculating Nr losses from any particular site or treatment. However, the intent of this study was to comparethe Nr losses and GHG emission of different management approaches on a very broad scale across crops and across regions, to determine if a high-yielding treatment that optimized N supply (ISSM) alsoreducedpotential Nr loss and GHG emission intensity. The soil, environmentalconditions, and N applicationmethodswere the same for all four treatments in each experimental site in each year.

In summary, reducing N surplus by both increasing crop uptake through measures that increase crop yieldand optimizing nutrient management should be a priority for scientists, policy-makers and farmers. In this study, the ISSM approachmatched N supply from thesoil and environment to N demand by the crops, through the right source, rate, timing, and placementof N fertilizer. At the same time, ISSM reduced N surplus by increasing grain yield throughbest management practices.This approach is particularly importantincountries/regions where N fertilizer is overused but the potential for yield increase is still high.

Supplementary Discussion –increasing yield while reducing environmental costs

To the extent that yields have already stagnated or reached yield plateaus in a large portion of the world's crop production area, current yield trends will not suffice to meet future demands on existing farmland[37]. Moreoptimistic projections of future grain production suggest that it would be possible to achieve a 40-70% increase in yieldsfor maize, wheat and rice globally by closing yield gaps[38,39].The yields in ISSM treatment we obtainedfrom these multi-sites/years field experiments (8.5, 8.9 and 14.2 Mg ha^{-1}), are comparable to what are considered to be yield potentials in the areas with the most favorable conditions and intensive agronomic management globally, and are 27%, 53% and 87% higher than those obtained in practice by Chinese farmers (6.7, 5.8, 7.6Mg ha^{-1}) (Table 1). The major factors explainingthe gap between our ISSM treatmentand farmers' practices are: (i) low efficiency of light and heat resource use due to low plant density, unsuitable sowing dates, short-duration varieties, and other poor crop management practices; (ii) poor nutrient and water management with either too largeor too small additions[40]. The potential for substantial gains in grain yield for maize, wheat and rice suggests an opportunity to meet food demandon existing farmland in China.

We found that a conventional"bottom-up" approach, which sought to overcome the main limiting factors for yield and nutrient use efficiency increase (treatment IP), succeeded in increasing crop yieldsand reducing environmental costs. However,an integrated soil-crop system management(ISSM) approach yielded significantly better results, indicating that agroecologicalinnovation in crop and soil management has great promise for increasing crop yield, improving the resource efficiency of agriculture, and greatly reducing harm to the environment[13]. This ISSM approach re-designedthe whole production system to reduce yield gaps while at the same time optimizingresource inputs like fertilizers, according to our modern understanding of crop nutrient demand, and root zone nutrient supply and losses[29].

Realizing the potential of agroecological innovations depends not only on progress in science and technology, but also on socioeconomic factors. We suggest that the reported"upper yield plateaus" for rice in China[41] maynot represent a biophysical yield limitation, but rather the prevalence ofextremely small farm sizes and growth in the proportion of part-time farmers. Forexample, in Heilongjiang province, Northeast China, the grain yield forrice in smallholding farmshas remained ata plateau since the mid-1990s.However, large-scale farms in the same regionmade use of new technologies and economies of scale to continuously increase yieldsoverthe past 10 years (Extended Data Figure 5).Interestingly, we foundabout 20% and 5% of rice and wheat farmers respectively report yields close to ISSM yields; for maize, even the top 5% farmers do not achieve yields close to ISSM (Extended Data Table 4). This information shows that the most successful farmers are not using excessive fertilizer; at least their practices are closer to ISSM or IP than to the HY treatments. We believe that with rapid economic development, urbanization, and changes in land tenure, innovative agricultural technologies canbe more widely adopted,and socioeconomic barriers to simultaneously increasing crop yield and mitigating environmental costsshould diminish.

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