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Scope and strategies for sustainable intensification of potato production in Northern China

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Abstract

Potato (*Solanum tuberosum*) is an important staple crop in China, however, potato yields are low, and thus a general aim is to produce more crop with fewer resources and minimal environmental effects. This study aimed to assess the relationships between yield, resource use efficiencies, and environmental performance of potato production in China. Three major potato production regions (Inner Mongolia, Gansu, and Heilongjiang) were surveyed. The current production performance was evaluated, and the scope for improvement was assessed based on a lower and upper target for yield (financial breakeven point and 85% of the potential yield, respectively), water productivity (upper target is 85% of the potential water productivity), nitrogen use efficiency (50 and 90%) and nitrogen surplus (upper target is 80 kg ha^{-1}). Long-term situations were evaluated to identify the target values of nitrogen use efficiency and nitrogen surplus based on currently available technologies. The results indicate that in the short-term nitrogen fertilizer input can be reduced by allowing for soil nitrogen mining to improve the nitrogen use efficiency and reduce nitrogen surplus. Water productivity can be increased by enhancing yield, and water surplus can be reduced by more efficient management of irrigation and rainfall water. In the long-term, with good agronomy, we assess it is feasible to improve yield (from 33–43 to 46–57 t FM ha^{-1}), improve nitrogen use efficiency (to 84%), and reduce nitrogen surplus (from 50–156 to 16–34 kg N ha^{-1}) simultaneously. The latter should be validated experimentally.

Abbreviations: DM, dry matter; ET, evapotranspiration; FM, fresh matter; IE, internal use efficiency of nitrogen; NHI, nitrogen harvest index; N surplus^{avail}, nitrogen surplus when soil N uptake (SNU) was added; NUE, nitrogen use efficiency; NUE^{avail}, NUE when SNU was added; RE, the recovery efficiency of N; REF, the recovery efficiency of N from N fertilizer; RETE, retention efficiency; RWS, reference weather station; SNU, soil N uptake; SOM, soil organic matter; WP, water productivity; WPa, actual water productivity; WPe, exploitable water productivity (85% of the potential water productivity); WPg, water productivity gap; Ya, actual yield; Ye, exploitable yield (85% of the potential yield); Yge, exploitable yield gap; Yp, potential yield; Yt, target yield.

1 INTRODUCTION

The concept of ecological footprint in agricultural production refers to the negative effects of food production on ecosystems (van Noordwijk & Brussaard, 2014). The resource use efficiency concept in agricultural production allows the connection of agronomic objectives (high yield and economic benefit) and environmental objectives (more output with less input and low environmental pollution; EU Nitrogen Expert Panel, 2015). The question whether food demand can be fulfilled while keeping the environmental effects at an acceptable level (sustainable intensification), has to be addressed for different cropping systems at various spatial-temporal scales (Cassman, 1999; van Noordwijk & Brussaard, 2014).

Agricultural production in China is associated with substantial inputs and undesirable environmental effects. The dominant type of nitrogen (N) input shifted from biological fixation and manure to synthetic fertilizers over the past 50 yr (Conant, Berdanier, & Grace, 2013). The excessive application of synthetic fertilizers resulted in large amounts of mineral N accumulated in the soil profile (up to 1230 kg NO_3–N ha^{-1} in 0- to 400-cm depth) in northern China (Fan, Hao, & Malhi, 2010). The accumulated mineral N may be permanently lost from the soil–plant system and constitutes a risk for environmental pollution (water contamination, greenhouse gas emission; Fan et al., 2010; Zhou, Gu, Schlesinger, & Ju, 2016; Zhu & Chen, 2002). Water resources for agricultural production are under increasing pressure because of high extraction rates, particularly in arid and semi-arid areas in the northern region of China (Deng, Shan, Zhang, & Turner, 2006).

Potato (*Solanum tuberosum*) is one of the most important noncereal crops in the world. China is the number one potato producing country in terms of total production (FAO, 2019). Potato in China is cultivated as cash crop which often receives large amounts of fertilizer input, and irrigation is needed in dry areas and in dry seasons of other areas to ensure yield and quality. With the rapid growth of the potato market for both table and processed products in China, intensive potato production systems are expanding. It is our assertion that potato production must be enhanced with sustainable practices that aim to produce more crop per hectare and use the available natural resources as efficiently as possible while minimizing undesirable environmental effects.

This study is the first to identify the relationships among yield, resource use efficiencies, and environmental effects of potato production in major potato production regions in northern China, and to assess the scope and strategies to enhance these simultaneously. First, the current system's performance was assessed, and the scope for improvement was evaluated based on target values in terms of yield, resource use efficiencies, and an environmentally safe upper limit for N surplus. Long-term situations of N fertilizer management and yield were then evaluated, considering currently feasible technologies, to derive future target values of nitrogen use efficiency (NUE) and N surplus, taking into account the long-term soil N dynamics. Finally, the strategies for improving yield, water use efficiency, and NUE and reducing water and N surplus under both short-term and long-term conditions are discussed.

Core Ideas

- Current and target yields, resource use efficiencies, and environmental effects were assessed.
- Currently, regions with higher yields have higher environmental effects, and vice versa.
- Potato yield and water productivity can be improved by 24% on average.
- The NUE was 47–68% excluding the SNU, and 32–45% including SNU.
- In the short-term, NUE can exceed 90%, but 84% is a feasible target in the long-term.

2 MATERIALS AND METHODS

2.1 Data collection

The study was conducted in three major potato producing regions in northern China: Inner Mongolia (a French fries processing factory), Gansu (a flakes processing industry), and Heilongjiang (a starch processing factory). For each region, farmers with a production contract with the local potato processing industries were interviewed during and after the potato growing season (Apr.–Sept.) in 2017 and 2018. Irrigation is commonly applied in Inner Mongolia (annual rainfall is between 78–470 mm; Li, Zhou, Wang, Shang, & Yang, 2019) and Gansu (39–783 mm; Yang et al., 2004), where all surveyed fields applied irrigation. In Heilongjiang, rainfall is considered sufficient (386–647 mm; Wang, Yang, & You, 2011), and irrigation was applied only in a few surveyed farms and fields (6 out of 21 farmers in 2017 and 6 out of 19 farmers in 2018).

The soil texture and chemical (soil organic matter, SOM; pH, total N, soil N uptake) parameters were measured for 14 fields in 2013 (after harvesting) and 15 fields in 2014 (before planting) in Inner Mongolia, and 75 fields in Heilongjiang in 2016 (before planting; Supplemental Tables S1, S2). The soil samples were taken for a depth of 0–25 cm, which is the ploughing depth of the surveyed regions. The soil samples were tested in the laboratory of Eurofins Agro, the Netherlands (http://eurofins-agro.com/nl-nl/). Soil characteristics were not measured for the surveyed fields in Gansu, and for this region we refer to soil analysis data from other studies available in the literature (Shang et al., 2012). The soil texture of the surveyed fields in Inner Mongolia was either sandy loam, loam or silt loam; in Gansu silt loam (Wang, Zhao, & Wu, 2010), and in Heilongjiang either clay loam, silty clay, or silty clay loam. For fields in Inner Mongolia and Heilongjiang, the soil N uptake was estimated from measured total N, C/N ratio, pH, and soil biological parameters by the Eurofins laboratory (Brolsma, personal communication, 2019). It is assumed to reflect the N uptake by plants from the soil mineral N supply in an unfertilized soil. The soil mineral N supply accounts for both mineral N (nitrate-N and ammonium-N) in the soil at the time of soil sample collection and mineralizable N from SOM becomes available as mineral N during the growing season. We refer to the lab-based soil N uptake as SNU.

The data and information concerning farm, field, potato variety, fertilizer, irrigation, and other management practices were collected during farmer interviews in 2017 and 2018. For Inner Mongolia, the data were collected by the local agronomists; the lead author also participated in the data collection. The data was collected from 25 farms in 2017 and 22 farms in 2018. Some farms were at the border of Inner Mongolia and Hebei province and belonged to Hebei from an administrative view; hereafter we refer to Inner Mongolia only, for brevity. The major potato variety was Innovator. Each farm had multiple fields, and in total 181 and 172 fields were surveyed in 2017 and 2018, respectively. The tuber fresh matter (FM) yield of each field was measured approximately 10 d before harvesting, by taking samples of 3 m along a ridge randomly selected in a land unit of 33.3 ha in each field (one sample was used for a field of maximum 33.3 ha; if the field was larger than 33.3 ha, multiple samples were collected and the average yield value of the land units was taken to represent the yield of an individual field). We verified whether the yield (t FM ha^{-1}) estimated by the 3-m samples represented well the total production for all fields per farm at harvest as measured in the factory (see Supplemental Figure S1). For each farm, irrigation amount (mm) per application was monitored (3–5 rain gauges were randomly allocated in the field and the average value was calculated) for one of the fields and assumed equal for the other fields sampled per farm). The daily rainfall over the growing season (from sowing to harvesting) was obtained at farm level (one or multiple rain gauges were allocated to each farm —usually close to the farmer's house—to monitor the daily rainfall).

In Gansu, 20 farms (65 fields) were interviewed in 2017, and 19 farms (28 fields) were surveyed in 2018 by the lead author. The major potato variety was Atlantic. In Heilongjiang, 21 farms (62 fields) were surveyed in 2017, and 19 farms (43 fields) were surveyed in 2018 by the lead author. Various potato varieties were planted such as Kexin, Yanshu, and Qingshu. For both regions, the yield data (in FM) was surveyed based on farmers' recall through a phone call after harvesting. Based on farmers' recall, the yield (t FM ha^{-1}) was estimated by dividing the total production of the field by the field area (or for a particular variety in the field if multiple varieties were planted). The total production was measured at the local processing factory when delivering the product. For both regions, irrigation type and amount (mm) per application were surveyed for each field based on farmers' recall (information such as duration of irrigation per application, water volume over time, and water volume per land area were collected). The daily rainfall of the surveyed regions in Gansu and Heilongjiang in the two years was obtained from online sources (NASA, 2019, for Gansu; National Meteorological Information Center, 2019, for Heilongjiang). For both regions, the weather station that was nearest to the surveyed regions was selected.

2.2 | Assessing yield, resources use efficiencies, and environmental effects

We used target values (upper and lower) for resource use efficiencies, and the environmentally safe threshold for N surplus based on the EU Nitrogen Expert Panel (2015) and model simulations. We defined the minimum N yield based on the yield at the economic breakeven point (lower target yield), and added a maximum N yield based on the exploitable yield (upper target yield, 85% of the potential yield, see the following section). The distance between current and target values in yield, NUE, and water productivity (WP) were identified to evaluate the scope for improvement. Based on our analysis using farm level data and accounting for the measured SNU, we provide suggestions for sustainable N fertilizer management in the short-term. In addition, taking into account the long-term soil N dynamics and currently feasible technologies, we provide suggestions for the NUE and N surplus targets in the long-term for potato production in northern China. Finally, we use the exploitable water productivity (85% of the potential water productivity, WPe) as targets for sustainable water management. The statistical analysis was performed using R Statistical Software.

2.3 | Yield

The average actual yield (Ya) was calculated per region per year. Potential yield (Yp) was defined as the yield obtained under non-water-limiting growing conditions (van Ittersum et al., 2013). The Yp was estimated per region per year using the World Food Studies (WOFOST) model (de Wit et al., 2019). The model was calibrated and validated based on a field experiment conducted in Heilongjiang for the Innovator cultivar (Wang, Reidsma, Pronk, de Wit, & van Ittersum, 2018). It estimates dry matter (DM) yield, which was converted to FM with a DM percentage of 20.8% (Wang et al., 2018). The weather data were obtained from online sources (National Meteorological Information Center, 2019, for Inner Mongolia and Heilongjiang; NASA, 2019, for Gansu) for the nearest weather stations (reference weather stations, RWS) to the surveyed area. For Inner Mongolia, two RWS were selected, whereas for Gansu and Heilongjiang, one RWS was used per region. For each year, two Yp estimations (based on the two RWS) were obtained for Inner Mongolia (average value was used to represent the Yp), and one Yp estimation (based on one RWS) was obtained for Gansu and Heilongjiang, respectively.

Although Yp is achievable theoretically, it is generally not cost-effective to obtain 100% of Yp due to the diminishing returns principle (Cassman, Dobermann, Walters, & Yang, 2003). Thus 85% of Yp (exploitable yield, Ye) was used as upper target yield for all regions (van Ittersum et al., 2013; www.yieldgap.org). The exploitable yield gap (Yge) was estimated as the difference between Ye and Ya (van Ittersum et al., 2013). The Yge was estimated per region and per year. The lower target yield was assumed the financial breakeven point (at this point the production neither makes profit nor suffers loss). As the breakeven point differs for different regions and for various production purposes (starch, flakes, and French fries processing) and the market price, the lower target yield (t FM ha^{-1}) was estimated based on production costs (renminbi [official currency of China, RMB] ha^{-1}) and sale prices (RMB t^{-1} FM) of surveyed farms per region.

2.4 | Water productivity and water surplus

Water productivity (WP), defined as the ratio between crop dry matter yield (kg DM ha^{-1}) and water use via evapotranspiration (ET, mm), represents the food production at the cost of water use in the hydrological domain (van Halsema & Vincent, 2012; www.yieldgap.org). Water productivity connects yield formation directly with crop water consumption and allows to compare across varieties, time, and locations. A lower WP implies more water evapotranspired to produce the same amount of DM. The actual water productivity (WPa) was calculated per region and per year as the ratio between actual tuber DM yield and the actual ET. The model estimates the potential ET, and we assumed that under non-water-limiting conditions, the actual ET equals the potential ET. The potential water productivity (WPp) was estimated per region and per year based on the Yp and potential ET. The exploitable water productivity (WPe) was estimated as 85% of WPp. It was used as the upper target for WP. The water productivity gap (WPg) was estimated per region and per year, as the difference between the WPe and WPa, to indicate the scope for improvement.

For potato growers in northern China, irrigation (irrigation water and irrigating) is one of the costliest management practices and requires a lot of labor, thus high water surplus implies unnecessary costs and waste of labor. To also address the waste part, the water surplus was estimated. Water surplus is proposed in this study as the water input minus actual ET per growing season (from sowing till harvesting). Water input included both irrigation water and rainfall during the growing season. The irrigation amount (mm) of surveyed fields was the sum of the irrigation volumes across all applications. Due to data limitations, plant available water in the soil at sowing was not considered in calculating water input. The average ET (mm), irrigation (mm), rainfall (mm), and water surplus (mm) were estimated per region and per year.

2.5 | Nitrogen use efficiency and nitrogen surplus

The input-output framework of NUE as proposed by the EU Nitrogen Expert Panel (2015) was used to evaluate the NUE and environmental effects of N use in potato production. The NUE was estimated based on the mass balance principle (Equations 1–3). NUE (kg kg^{-1}) was defined as the ratio between N output and N input.

$$\text{N input} = \text{N fertilizer} + \text{N deposition} \tag{1}$$

$$\text{N output} = \text{N removed in harvested product} \tag{2}$$

$$\text{N surplus} = \text{N input} - \text{N output} = \text{N losses} + \text{change in soil mineral N supply} \tag{3}$$

$$\text{N}^{\text{avail}} = \text{N input} + \text{soil N uptake} \tag{4}$$

$$\text{N surplus}^{\text{avail}} = \text{N surplus} + \text{soil N uptake} \quad (5)$$

N^{avail} indicates the total amount of available N after accounting for the SNU as N input; N $surplus^{avail}$ indicates the N surplus after accounting for the SNU as N input. Based on the framework, the N input (kg ha^{-1}; Equation 1) is the total amount of N that enters the field via fertilizer and atmospheric deposition. The only N fertilizer used in the study regions was mineral fertilizer (often urea 46–0–0 and/or compound fertilizer with various combinations of NPK). Organic fertilizer was not applied in any of the surveyed fields. The N input from atmospheric deposition (kg ha^{-1} yr^{-1}) for the three regions was assumed equal to the estimation by Xu, Luo et al. (2015) for the northeast (Heilongjiang, 28 kg ha^{-1}) and the northwest (Inner Mongolia and Gansu, 19 kg ha^{-1}) of China.

The N output (kg ha^{-1}; Equation 2) was the N removed from the field with the harvestable product (tubers), and was calculated based on tuber FM yield (kg FM ha^{-1}), a default DM percentage (20.8%; Wang et al., 2018) and an assumed N concentration in dry tubers (1.62%). The N surplus (kg ha^{-1}; Equation 3) is the difference between N input and N output. It consists of N losses (N leaching, N runoff, and gaseous N losses such as NH_3, N_2, NO_x), and changes in the soil mineral N supply. N surplus is a critical component in judging the environmental effect (EU Nitrogen Expert Panel, 2015). The average N input, N output, NUE, and N surplus were assessed for each of the fields surveyed per region and per year.

The upper target value for NUE was assumed to be 90% for all regions and years, implying very efficient use of N fertilizer (EU Nitrogen Expert Panel, 2015). A NUE higher than 90% may be associated with soil mining, but this need not be problematic in regions with high soil mineral N supply or could even be desirable to decrease the risk of N losses. We defined the NUE gap as the difference between the upper target NUE value (90%) and the actual NUE and calculated its value per region and per year. The lower target value of NUE was assumed to be 50%, and the upper target value for N surplus was assumed to be 80 kg ha^{-1} (EU Nitrogen Expert Panel, 2015). These values were assumed the same as tentatively set for Europe. We use these target values as a starting point and will discuss their relevance for potato production in northern China when considering long-term soil N dynamics and currently available technologies.

The soil mineral N supply is not considered as N input by the EU Nitrogen Expert Panel framework as it is assumed stable over years (thus the change in soil mineral N supply [Equation 3] is small and N surplus reflects the N losses well). However, we argue that it should be taken into account in giving short-term recommendations if current soil mineral N supply is high due to high SOM (which will inevitably decrease in time under arable cropping), and excessive past mineral N fertilizer or manure use (thus soil mineral N supply changes over years, and N surplus reflects N losses correctly only if the net change in soil mineral N supply over years is considered). The SNU by the crop was estimated for fields in each region (Supplemental Table S1, see Data collection). To account for the variation in SNU, the average, 5th or 95th percentiles of SNU per region and year (Supplemental Table S2) were added to the N input, to arrive at the total amount of available N (N^{avail}; Equation 4). With this amount as reference, the corresponding NUE and N surplus are denoted as NUE^{avail} and N $surplus^{avail}$ (Equation 5), respectively.

2.6 | Assessing yield, nitrogen use efficiency, and environmental effects for current conditions (short-term)

Relationships between N input, N output, NUE, and N surplus were expressed in scatter plots for the three regions and the two years. This was done without (Current Situation I) or with (Current Situation II) considering the measured soil N uptake (for the average, 5th and 95th percentiles of SNU) as N input. Note, that for Current Situation I, the terms related to soil N were removed from Equations 3–5. For Current Situations I and II, the target values for yield (lower and upper yield target), NUE (50 and 90%), and N surplus (80 kg ha^{-1}) were visualized in the plots. It should be noted that the upper and lower targets of NUE (90 and 50%) and N surplus (80 kg N ha^{-1}) were defined for a soil N supply in equilibrium, which is not the case in our conditions. Thus, these targets should not be used when including SNU in the total N input, but we use them as a reference to allow direct comparison of NUE and N surplus between the Current Situations I and II. For Current Situation I, the proportion of fields that meets the lower target values for yield (yield > lower target yield), resource use efficiency (NUE > 50%), and the environmental effect (N surplus < 80 kg ha^{-1}) were identified for each region (of two years jointly). This assessment was not performed for Current Situation II, as the target values (NUE and N surplus) should be changed when SNU is considered. The compromise between achieving acceptable levels of yield, NUE, and environmental effects (N surplus) provides a basis for improved strategies of N fertilizer management in the short-term.

2.7 | Evaluating long-term situations

Earlier we showed a large scope for improving potato yield in northern China (Wang et al., 2018). To understand whether and how sustainable intensification can be achieved, we chose two situations that aim at different target yields, that is, current yield level (Ya), and a higher yield level (Ye). We considered long-term soil N dynamics and currently available technologies to estimate the optimal feasible NUE and N surplus in the long term. The annual N input requirement (from N fertilizer input and N deposition) was estimated for the different target yields based on a simple equilibrium model developed by Ten Berge et al. (2019). The model assumed that under highly efficient N management, a given target yield can be sustained by an annual total N input (AT; from both fertilizers and atmospheric N deposition) that is equal to the corresponding annual total crop N uptake (UT). Another assumption is that in the long term, the soil mineral N supply is constant (steady state equilibrium), which means that once equilibrium has been reached, the outflow from the soil mineral N supply (annual N mineralization) is equal to the annual inflow. The latter inflow is expressed as a fraction (retention efficiency, RETE) of all N that becomes available for uptake but is not exported in harvested product: non-absorbed fertilizer-N, non-absorbed N from the soil mineral N supply, and N in crop residues. For simplicity, we assumed a potato monoculture as crop rotation.

To fulfill the above condition (AT = UT), the recovery efficiency of N from N fertilizer (REF), the recovery efficiency of N from the soil mineral N supply (RES), and the RETE all have to be maintained at a certain high level. Based on the principle of the response of yield to the interactions between different macronutrients (N, P, K; Janssen et al., 1990), Ten Berge et al. (2019) developed a protocol to estimate the recovery efficiency of N (RE) and internal use efficiency of N (IE) for a target yield for a balanced nutrient supply (N, P, K) and non-nutrient limited production. An initial value of RE and IE is assumed for a situation when the nutrient (in our case, N) is managed most efficiently and the macronutrients (N, P, K) are in balanced supply (medium dilution; Ten Berge et al., 2019). With highly efficient N fertilizer management, the REF for the potato crop was assumed to be 55% (Vos, 2009). This value refers to production practice in Europe at economically optimum N fertilizer input. The RES was assumed to be equal to the REF. The IE of potato was assumed 71.5 kg tuber DM per kg crop N uptake (Janssen, 2017; Ten Berge et al., 2019). Both RE and IE are assumed constant (the initial values), regardless of the target yield (Yt) when the ratio between the Yt and the Yp (Yt/Yp) is below a critical value (Supplemental Figure S2). Beyond that critical yield ratio, both RE and IE decrease following a quadratic relationship and become zero when the Yp is obtained (Yt/Yp = 1; Supplemental Figure S2).

Based on the approach described by Ten Berge et al. (2019) and data from Janssen (2017) and Vos (1997), RE and IE for different target yields (Ya and Ye) in the three regions were estimated (Supplemental Table S3). The N concentration in tuber dry matter of the two target yields was based on a fixed nitrogen harvest index (NHI = 84%; Janssen, 2017; Velthof & van Erp, 1999) and on IE. A fixed NHI was assumed based on data from Janssen (2017) and Vos (1997) and the harvest index (HI) for the potato dry matter was assumed .87 for both yield targets (Vos, 1997). Having set these parameters, it follows that to fulfill the assumptions of the simple equilibrium model, the RETE attains the value of 86 and 88% for Ya and Ye, respectively (Supplemental Table S3). The N input, N output, NUE, and N surplus for the two target yields (Ya and Ye) in the long-term situation were identified and compared with those derived from the Current Situation I (2018) for the three regions.

3 | RESULTS

3.1 | Yield

The average Ya of the surveyed regions over 2 yr was 37.4 t FM ha^{-1} (Table 1). The average Ya in Inner Mongolia (40.5 t FM ha^{-1}) and Gansu (40.7 t FM ha^{-1}) was higher than that in Heilongjiang (31.2 t FM ha^{-1}). The average Ya in all three regions was higher than the lower target yields in both years (Table 1). The percentage of fields that meet the lower target value for yield in the three regions (based on all year and field combinations) was 74% in Inner Mongolia, 88% in Gansu, and 76% in Heilongjiang (Figure 1). The average Yp across all regions and years was 51.8 t FM ha^{-1} (Table 1). The Yp in Inner Mongolia and Gansu was higher than that in Heilongjiang in both years, reflecting more favourable climatic conditions for potato production in the two regions (i.e., lower temperature). There was a large scope for improving yield in all regions (the average relative Yge was 24%).

3.2 | Water input, water productivity, and water surplus

The irrigation amount was highest in Gansu and lowest in Heilongjiang in both years, where rainfall was lowest in Gansu and highest in Heilongjiang (Table 1). For all regions and years, the total water input was much higher than the estimated ET (Table 1). The water surplus was highest in Gansu in both years due to the high irrigation input, implying that water was not used efficiently and was lost through runoff and/or deep drainage. The WPa was lowest in Heilongjiang in both years due to the low Ya obtained in the region. For the three regions, WP can be

TABLE 1 The current production performance and the scope for improvement in terms of yield (actual, Ya; potential, Yp; exploitable yield, Ye; yield gap, Yge; relative Yge), water use (irrigation; rainfall; total water input; evapotranspiration, ET; water surplus), and water productivity (actual WP, WPa; exploitable WP, WPe; WP gap, WPg; relative WPg) of three regions in 2 yr

	2017			2018			
Parameter	Inner Mongolia	Gansu	Heilongjiang	Inner Mongolia	Gansu	Heilongjiang	Average
Ya, t FM[a] ha^{-1}	38.3 (9.6)[b]	38.8 (6.8)	29.7 (6.9)	42.6 (8.4)	42.5 (7.1)	32.6 (11.9)	37.4 (8.4)
Lower target yield, t FM ha^{-1}	35	32	27	35	32	27	31
Yp, t FM ha^{-1}	59.4	63.2	44.2	57.7	67.3	54.3	51.8
Ye, t FM ha^{-1}	50.5	53.7	37.6	49	57.2	46.2	49
Yge, t FM ha^{-1}	12.2	14.9	7.9	6.4	14.7	13.6	11.6
Relative Yge, %	24 (19)	28 (13)	21 (18)	13 (17)	26 (12)	29 (26)	24 (18)
Irrigation type	Sprinkler	Flooding	Rainfed/sprinkler	Sprinkler	Flooding/drip	Rainfed/drip	
Irrigation, mm	302	767	45	275	588	70	341
Rainfall, mm	203	91	316	266	95	501	245
Total water input, mm	505	858	323	541	684	513	571
ET, mm	266	288	271	256	269	269	270
Water surplus, mm	239	570	52	285	415	244	301
WPa, kg DM[a] ha^{-1} mm^{-1}	30	28	23	35	33	25	29
WPe, kg DM ha^{-1} mm^{-1}	40	39	29	40	44	36	38
WPg, kg DM ha^{-1} mm^{-1}	10	11	6	5	11	10	9
Relative WPg, %	24	28	21	13	26	29	24

[a]FM, fresh matter; DM, dry matter.
[b]Values in parentheses are standard deviation.

increased to 29–44 kg DM ha^{-1} mm^{-1} (WPe) by enhancing yield. Water surplus can be reduced by more efficient management of irrigation and rainfall water (drip irrigation, mulching). It should be noted that the initial soil water content at sowing was not taken into consideration when estimating total water input, and thus the water surplus may have been underestimated or overestimated.

3.3 | Nitrogen input, nitrogen use efficiency, and nitrogen surplus (short-term)

Both N fertilizer and total N input (including N deposition) were highest in Inner Mongolia, lowest in Heilongjiang, and intermediate in Gansu (Table 2). For the Current Situation I (SNU was excluded from N input), the average NUE across years in Gansu (51%) and Heilongjiang (68%) were above the lower target value of NUE (50%), whereas NUE in Inner Mongolia (47%) was below that target (Table 2). The N surplus in Inner Mongolia (156 kg N ha^{-1}) and Gansu (132 kg N ha^{-1}) was beyond the target value (80 kg ha^{-1}), whereas N surplus in Heilongjiang (50 kg N ha^{-1}) was well below the target. The percentage of fields that met the lower target NUE (50%) was 33% in Inner Mongolia, 48% in Gansu, and 88% in Heilongjiang; and the percentage of fields that met the target N surplus (80 kg ha^{-1}) was 3% in Inner Mongolia, 32% in Gansu, and 77% in Heilongjiang (Figure 1a, 1c, 1e).

The SNU was estimated to vary largely across fields within a region (Table 3). It was much higher in Heilongjiang than in the other two regions. The average SNU in Heilongjiang was higher than the N output, indicating that N fertilizer could be omitted in the short-term, perhaps without compromising yield. For Current Situation II (various SNU values were added to N input), the data points move towards the right, further away from the desired space (Figure 1b, 1d, 1f). The average NUE^{avail} (between 32 and 45%) became lower for all three regions, but particularly for Heilongjiang, and the average N $surplus^{avail}$ became higher (128–265 kg ha^{-1}). The differences in NUE^{avail} across different regions became smaller, yet N $surplus^{avail}$ was still higher in Inner Mongolia than in the other two regions (Table 3).

3.4 | Evaluating different situations based on the long-term soil nitrogen balance

For Inner Mongolia, following our long-term approach, the N fertilizer requirement for both target yields (for Ya, 126 kg ha^{-1}; for Ye, 167 kg ha^{-1}) was much less than the actual N fertilizer input in 2018 (276 kg ha^{-1}; Table 4).

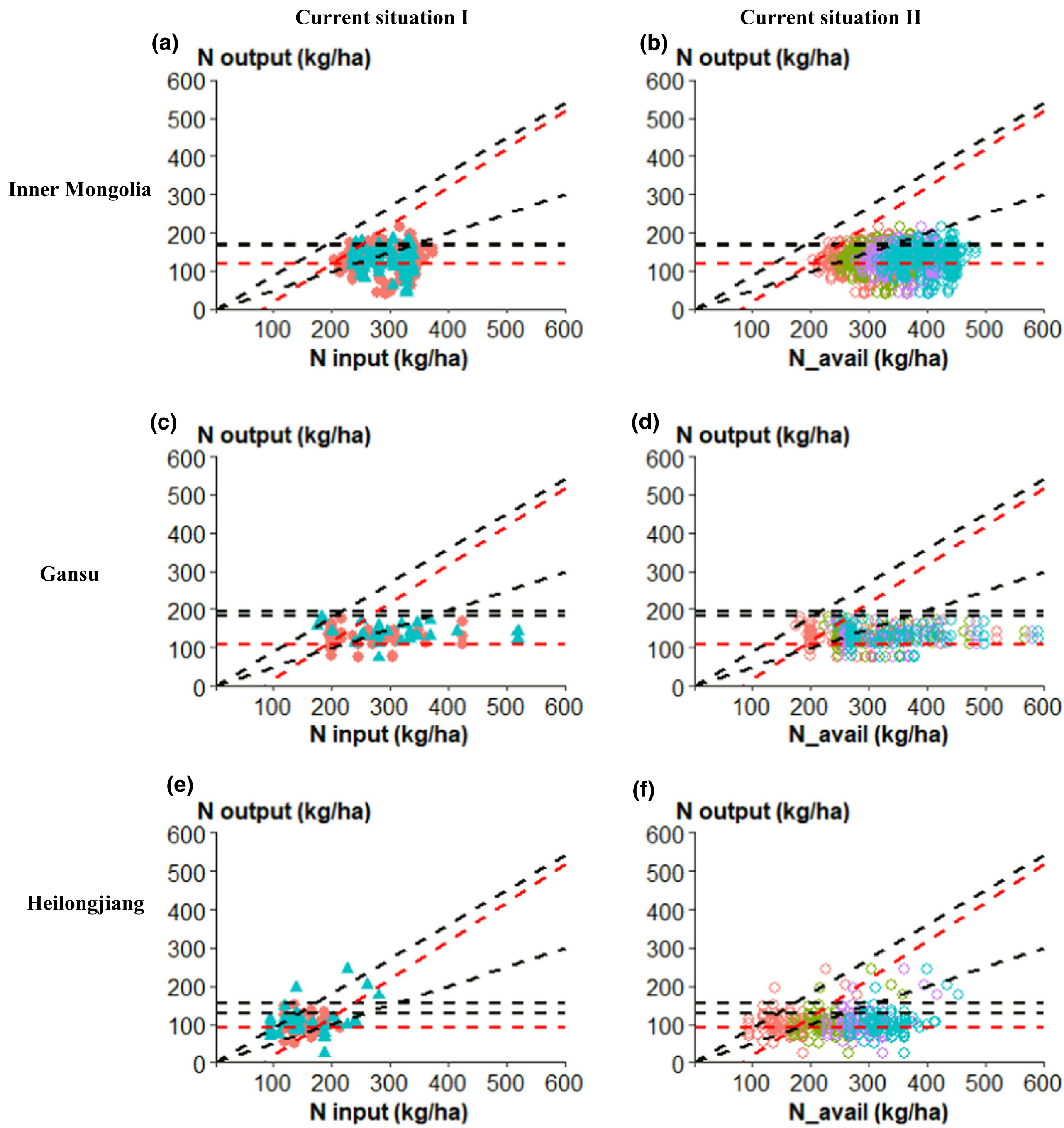

FIGURE 1 The nitrogen (N) balance of potato production (N input, N output, nitrogen use efficiency (NUE) and N surplus) in Inner Mongolia (a, b), Gansu (c, d) and Heilongjiang (e, f) and two years (2017, 2018). In the Current Situation I, (a, c, e), the soil N uptake (SNU) was not considered in N input, and different colors indicate different years (red 2017, blue 2018). In the Current Situation II, (b, d, f), the various values of SNU (0, 5th, average, and 95th SNU) were included in the N input for 2017 and 2018 jointly, and different colors indicate various SNU (red 0, green 5th, purple average, and blue 95th SNU). The two black horizontal dashed lines indicate, respectively, the upper target level for N output per region for 2017 and 2018 (calculated based on 85% of the Yp per region per year) and the red horizontal dashed line indicates the lower target levels of N output per region (calculated based on the lower target yield for each region). The black diagonal dashed lines indicate the upper (90%) and lower (50%) target values for NUE. The red diagonal dashed lines indicate the target level for N surplus (80 kg ha^{-1})

When the target yield approaches Yp, both the recovery efficiency and internal use efficiency decreased (REF was 0.55 for Ya and 0.52 for Ye; IE was 62 kg DM kg^{-1} N for Ya and 55 kg DM kg^{-1} N for Ye; Supplemental Table S3). Therefore, the agronomic efficiency of N fertilizer (i.e., the gain in dry matter yield per unit of N fertilizer input) decreased with a yield increase from Ya to Ye, and thus the requirement for N fertilizer increased. Compared to Current Situation I (2018), the NUE increased from 49 to 84% for both target yields (Ya and Ye), and N surplus decreased

TABLE 2 The nitrogen (N) balance of potato production in the three regions in two years (2017 and 2018). The N input, N output, nitrogen use efficiency (NUE) and N surplus without considering the measured soil N uptake (SNU) (Current Situation I)

Regions	N fertilizer	N deposition	Total N input	N output	NUE	Upper target NUE	NUE gap	N surplus
	kg ha^{-1}				%			kg ha^{-1}
Inner Mongolia	273	19	292	137	47	90	43	156
Gansu	250	19	269	138	51	90	39	132
Heilongjiang	127	28	155	105	68	90	22	50

TABLE 3 The nitrogen (N) balance of potato production in the three regions in two years (2017 and 2018). The N input, N output, nitrogen use efficiency (NUE) and N surplus considering the measured soil N uptake (SNU) (Current Situation II)

Regions	SNU	SNU	N fertilizer	N deposition	Total available N	N output	Available NUE	Available surplus N
		kg ha^{-1}					%	kg ha^{-1}
Inner Mongolia	5th	37	273	19	329	137	41	193
	Average	74	273	19	366	137	37	230
	95th	109	273	19	401	137	34	265
Gansu	5th	43	250	19	312	138	44	175
	Average	68	250	19	337	138	41	200
	95th	91	250	19	360	138	39	223
Heilongjiang	5th	78	127	28	233	105	45	128
	Average	136	127	28	291	105	36	186
	95th	174	127	28	329	105	32	224

from 151 to 23 and 29 kg ha^{-1} for Ya and Ye, respectively. The increase in NUE (N output/N input) and the decline in N surplus (N input − N output) can be attributed primarily to the reduced N fertilizer input (Table 4). The higher N output in the current situation than in the long-term situation, for the same target yield (Ya) was due to the lower N concentration in tuber dry matter for the long-term situation (1.38 and 1.54% for Ya and Ye, respectively; Supplemental Table S3) than the current situation (1.62%), in which the N is accumulated due to the excessive supply of N fertilizer and limitation of other growing factors (Janssen et al., 1990).

For the Gansu region, the N fertilizer requirement was 113 and 198 kg ha^{-1} for Ya and Ye, respectively. Compared to the Current Situation I (2018), in the long-term situation the NUE increased from 49 to 84% for both Ya and Ye, and N surplus declined from 151 to 21 kg ha^{-1} for Ya and to 34 kg ha^{-1} for Ye. The REF was 0.55 for Ya and 0.52 for Ye; IE was 68 kg DM kg^{-1} N for Ya and 55 kg DM kg^{-1} N for Ye (Supplemental Table S3).

For the Heilongjiang region, in the long-term, the N fertilizer requirement was 70 and 148 kg ha^{-1} for Ya and Ye, respectively. Compared to the Current Situation I (2018), the NUE increased from 72 to 84% for both Ya and Ye. N surplus decreased from 42 to 16 kg ha^{-1} when targeting Ya, and to 27 kg ha^{-1} when targeting Ye. The REF was 0.55 for Ya and 0.52 for Ye; IE was 70 and 55 kg DM kg^{-1} N for Ya and Ye, respectively (Supplemental Table S3).

The results suggest that even when increasing yields to Ye, N input can be reduced, NUE increased, and N surplus reduced in Inner Mongolia and Gansu, but in Heilongjiang larger N inputs may be needed for Ye (Table 4). Compared to Ya, the yield target Ye is 13–29% higher across regions in the long-term situation, whereas the N surplus increased by 26–69%, indicating a trade-off between yield and environmental effect.

4 | DISCUSSION

4.1 | Yield

The yield obtained by surveyed farmers (37.4 t FM ha^{-1}) was much higher than the average value of the country (17 t FM ha^{-1} in 2017; FAO, 2019). The seed tuber quality, technology, and mechanization level of the surveyed farms were superior to that of smallholder farmers in northern China. However, the Ya was still lower than the Ye estimated by the model. The major yield constraints for potato production in China are poor seed tuber quality (Inouye, 2018), limited availability of potato varieties for various production purposes (Jansky, Jin, Xie, Xie, &

TABLE 4 The nitrogen (N) balance in the Current Situation I (2018) and the long-term situations with two target yields (actual yield, Ya; exploitable yield, Ye) of the three regions. The N output, N input requirement (sum of N fertilizer and N deposition), nitrogen use efficiency (NUE) and N surplus

Regions	Situations	Target yield	Target yield	N input: N fertilizer	N input: N deposition	N input: Total N input	N output	NUE	N surplus
			t FM ha^{-1}	kg ha^{-1}				%	kg ha^{-1}
Inner Mongolia	Current Situation I	Ya	42.6	276	19	295	144	49	151
	Long-term	Ya	42.6	126	19	145	122	84	23
	Long-term	Ye	49.0	167	19	186	157	84	29
Gansu	Current Situation I	Ya	42.5	275	19	294	143	49	151
	Long-term	Ya	42.5	113	19	132	111	84	21
	Long-term	Ye	57.2	198	19	217	183	84	34
Heilongjiang	Current Situation I	Ya	32.6	124	28	152	110	72	42
	Long-term	Ya	32.6	70	28	98	82	84	16
	Long-term	Ye	46.2	148	28	176	149	84	27

Spooner, 2009), and unbalanced nutrient supply (Duan, Tuo, Zhao, Li, & Li, 2013). For the surveyed regions, poor soil conditions (compaction, shallow plough layer, lack of micronutrients), insufficient production inputs (machinery, labour, irrigation), and various pest and diseases problems (potato wilt, scab, late blight, early blight, etc.) were the major production constraints according to local agronomists and farmers (personal communications). In this study, a default DM percentage (20.8%) was assumed for different varieties and various production purposes (French fries, flakes, starch). The Yp, and the yield gap may be slightly different if different DM percentages for specific varieties were considered.

4.2 | Water use efficiency, water input, and water surplus

The ET (256–266 mm) and the WPe in Inner Mongolia (40 kg DM ha^{-1} mm^{-1}) estimated in our study were close the values obtained by Jia, Qin, Chen, and Fan (2018; ET = 259 mm, WP = 37.4 kg DM ha^{-1} mm^{-1}). The practice of covering land with plastic mulch is commonly applied in the surveyed farms in Gansu in order to reduce evaporation and maintain soil moisture. Despite this water-saving practice, water input and water surplus observed in Gansu was still high. With flooding irrigation, the total water input in the growing season is usually far above the ET requirement, whereas potato growth may still be limited due to water stress (Li, Duan, Guo, & Zhang, 2011). Sprinkler irrigation and drip irrigation consume much less water than flooding irrigation (Song, Wang, Yang, & Yang, 2013). In Inner Mongolia, the total water input was higher than the ET in both years, yet water stress was observed by local farmers in some of the fields (based on farmers' interviews). This reflects the inefficient use of water (rainfall and irrigation) and loss of water resources (via run-off and deep drainage). Irrigation should be managed more efficiently tailored to the water requirements of the crops in specific growth stages. For Inner Mongolia and Gansu specifically, more efficient irrigation system (drip irrigation) is recommended to reduce irrigation water input and water surplus and to improve crop yield and water use efficiency.

4.3 | Nitrogen use efficiency, nitrogen input, and nitrogen surplus (short-term)

For the Current Situation I (SNU was not considered as N input) the average NUE observed for potato production in northern China (47–68% in different regions) was generally at a moderate level, whereas the N fertilizer input in the surveyed fields was 66–500 kg N ha^{-1}. A higher NUE (above 90%) was observed in field experiments in the Netherlands with N fertilizer input of 100 to 250 kg N ha^{-1} under fertigation conditions (SNU was also excluded; EU Nitrogen Expert Panel, 2015). Only in Heilongjiang region, a few fields with low N fertilizer input (less than 150 kg ha^{-1}) obtained a NUE above 90% (Figure 1e).

In the EU Nitrogen Expert Panel framework, soil mineral N supply was not considered as N input, which is defendable under the assumption that the soil mineral N supply can be considered stable over years. However, there is a lack of regulation on maximum N fertilizer input in crop land in China, and farmers tend to apply excessive amounts of N fertilizer to push the yield boundary (Liu et al., 2011; Xu, Liu et al., 2015; Zhou et al., 2016). For instance, the N fertilizer input was as high as 700 kg N ha^{-1} for large-scale commercial potato production in Inner Mongolia approximately 10 yr ago and gradually reduced to the current level (200–300 kg N ha^{-1}; Wang, personal communication, 2018). In addition, soils in regions such as Heilongjiang have high SOM contents which will decline with long-term arable farming. Thus, it may be assumed that the soil mineral N supply is also currently in transition and will decline over the years. Under such conditions, the soil mineral N supply should be considered if the purpose of the analysis is to compare the production performance of different farms and monitor the change of a system over time. For comparative purpose, we have therefore included the SNU. However, for a fair comparison, the soil mineral N supply in the long-term equilibrium should be subtracted from the current soil mineral N supply. The resulting estimate provides the additional soil mineral N supply which is essentially related to the N losses. This long-term soil mineral N supply can be estimated by the model of Ten Berge et al. (2019) which we used, but depends on several assumptions, and was therefore not presented.

In addition, the target values (upper and lower targets of NUE and N surplus) should be changed accordingly when soil mineral N supply is considered. The target values that we used were tentatively set by the EU Nitrogen Expert Panel framework. Quemeda et al. (2020) suggested to use the first and third quartile of NUE to set lower and upper boundaries. These can be used to compare different farms and can be easily adopted. These are empirical values however, and do not necessarily relate to environmental effects.

For the Current Situation II, when SNU was added to the N input, the NUE was low and N surplus was high (Table 3). For the three surveyed regions, in the short-term, it was possible to improve NUE and reduce N surplus by reducing N fertilizer input and allowing soil mining. In Heilongjiang specifically, some fields have enough SNU to support the current average yield (Table 3). The scope to further reduce N fertilizer input depends on SNU, target yield, and the achievable recovery efficiency of N fertilizer. The short-term recommendations for N fertilizer input for specific fields should be based on reliable assessment of the SNU per field, which should thus be evaluated via on-farm field experiments, including control treatments without N fertilizer input.

The N surplus estimated in this study (on average 50–156 kg ha^{-1} when SNU was not considered) is similar to that observed in farmers' fields for wheat (89 kg ha^{-1}) and maize (87 kg ha^{-1}), but much lower than that of vegetable (356 kg ha^{-1}) and orchard fields (464 kg ha^{-1}) in the North China Plain (Zhou et al., 2016). It was found that the major pathway of N losses in the arid and semi-arid area in northern China is through nitrate leaching and ammonia volatilization (Fan et al., 2010). The negative influence of N leaching on groundwater is limited in regions where the groundwater table is deep (Ju, Kou, Zhang, & Christie, 2006). However, due to the large N surplus, a substantial amount of nitrate enters the vadose zone (below the root zone and above the ground water surface), where denitrification is limited due to the high oxygen concentration, lack of carbon sources, and limited biological activity. The leached nitrate will gradually move downwards via intensive precipitation and irrigation (flood irrigation) and eventually threaten the groundwater quality (Fan et al., 2010; Ju et al., 2006; Zhou et al., 2016). Thus, a large N surplus is not only an economic loss to the growers but also a potential risk to the environment in the long term.

4.4 | Different situations based on the long-term soil nitrogen balance

In the long-term, the estimated NUE was the same in both yield situations (Ya and Ye) in all regions (84%; Table 4) because N input requirement was assumed equal to the crop N uptake for the target yield (Ten Berge et al., 2019). Therefore, NUE (the ratio between N output, i.e., N uptake in tubers, and N input) is equal to the NHI (the ratio between N uptake in tubers and N uptake in the whole crop, which is equal to the N input). The NHI was assumed to be the same for the two target yields (84%; Janssen, 2017; Velthof & van Erp, 1999; see Materials and Methods section). However, it should be noted that the NHI may be different for different potato cultivars, and different values for NHI have been observed. High values of 88% (Vos, 1997) and 85% (Biemond & Vos, 1992) have shown to be feasible, but current NHI in China ranges between 43 and 91%, with an average of 64% (Xu et al., 2019), similar to what we found in our dataset.

Although NUEs above 90% are feasible in the short-term thanks to a high soil N supply, when considering long-term soil N dynamics and currently available technologies, our results suggest a maximum NUE of 84%. To fulfill the long-term equilibrium conditions, the N resources (from fertilizer, soil, and crop residues) should be managed highly efficiently (REF was assumed 55% for Ya and 52% for Ye; Supplemental Table S3; and RETE was estimated 86% for Ya and 88% for Ye; Supplemental Table S3). It should be noted, however, that a RETE of 86 to 88% may be difficult to achieve and maintain for the potato crop. Also, the REF obtained in experimental fields in Inner Mongolia ranged between 29 and 50% for potatoes in irrigated conditions (Duan et al., 2013), and only the maximum value (50%) approached the value we assumed for the initial REF (55%). Therefore, our estimations of NUE and N surplus are likely to be optimistic and must be verified experimentally, but they provide a benchmark based on literature and available empirical data, mostly for Dutch conditions.

We assumed a monoculture in modelling N; currently farmers do not employ a fixed rotation scheme. Yet, we recognize that for sustainable potato production, the crop should be rotated with cereal and non-cereal crops (maize, wheat, soybean, sunflower [*Helianthus* L.]) in a regular scheme. Proper rotation with such deep-rooting crops that can access the mineral N accumulated in deeper soil layers may improve RETE of the whole system. Ideally, the whole system must be considered when evaluating the system performance (in terms of yield, NUE, N surplus) by performing long-term field experiments and/or model simulations.

4.5 | Targets for sustainable intensification

The EU Nitrogen Expert Panel set a lower target level for N yield of 80 kg N ha^{-1}. We adapted this lower target level to the economic breakeven yield, which was 91–118 kg N ha^{-1} for potato in the three surveyed regions in China. The Ye can be used as an upper target for further intensification, corresponding to an average yield increase of 24% (relative Yge), to 37.6–57.2 t FM ha^{-1} (127–193 kg N ha^{-1}), depending on the year and region. The WPe was 29–44 kg DM ha^{-1} mm^{-1}. The water surplus can be reduced, although temporal variability in water availability could still cause water stress, depending on initial soil water availability and weather variability. Many potato fields in northern China (Inner Mongolia and Gansu) performed below the lower NUE target of 50% (Figure 1a, 1c). In the short term, an NUE target (without considering SNU) of 90% or even higher is feasible on some farms in Heilongjiang, as soil mineral N supply is high due to the decomposition of SOM. The long-term situations showed that with currently available techniques, an NUE of 84% is a feasible target in the long term for both Ya and Ye. A high REF (55% for Ya and 52% for Ye) and RETE (86% for Ya and 88% for Ye) are needed to make a NUE of 84% feasible in the long term. Our N surplus values of 27–34 kg N ha^{-1} in the long-term situation and Ye are much lower than the EU target of 80 kg N ha^{-1}.

5 | CONCLUSIONS

This study evaluated the current production performance in terms of yield, NUE, and WP and the scope to improve these simultaneously for potato production in northern China (Inner Mongolia, Gansu, and Heilongjiang). Farmers in Inner Mongolia and Gansu obtained higher yield than in Heilongjiang. Farmers in Inner Mongolia obtained highest N surplus, whereas those in Heilongjiang obtained lowest N surplus and water surplus due to the lower resource inputs. Farmers in Gansu obtained high water surplus due to the excessive irrigation water input. There was significant scope to improve yields, that is, from 37.6 to 57.2 t FM ha^{-1} in the different regions. The WP can be improved from 23–35 to 29–44 kg DM ha^{-1} mm^{-1}. Smarter irrigation systems (drip irrigation) are needed to improve WP and reduce water surplus. The current NUE was moderate and N surplus was high (when the SNU was excluded, NUE was 47–68% and N surplus was between 50–156 kg ha^{-1}; when SNU was added, NUE^{avail} was only 32–45% and N surplus^{avail} was 128–265 kg ha^{-1}) due to the high N fertilizer input and high SNU. In the short-term, NUE (without accounting for SNU) can be largely increased to above 90% due to a high SNU, and N surplus can be reduced by improving the yield and/or reducing N fertilizer input. The evolution in soil N uptake should be considered for proper N fertilization. In the long term, with good agronomy including efficient nutrient management and avoidance of weeds, pests, and diseases, our results suggest it is possible to narrow the yield gaps and reduce the efficiency gaps and environmental effects at the same time. The upper target value of NUE (90%) and N surplus (80 kg ha^{-1}) as applied by EU Nitrogen Expert Panel have been evaluated by considering long-term N dynamics and currently available technologies. For the potato crop in northern China, the estimated NUE in the long-term situation for the Ye under most efficient N management was 84%, and N surplus was 27–34 kg ha^{-1}, which could be used as updated targets for the long term. These results must be verified experimentally with detailed measurements of nitrogen balances.

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DECLARATION ON CONFLICT OF INTEREST

The authors declare that there is no potential conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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