Chapter 14
Evaluating Resource Use Efficiency and Stock Balances of Nitrogen and Phosphorus Fertilizer Inputs: The Effect of Soil Supply Capacity in Tigray (Ethiopia)

Richard G. Kraaijvanger and Tom Veldkamp

Abstract In sub-Saharan Africa crop productivity is generally low, which affects food security and livelihoods. The application of mineral fertilizers in many cases is seen as a straightforward way to improve crop productivity. In Tigray, Northern Ethiopia, agricultural extension bureaus recommend the application of considerable amounts of fertilizers. Farmers, however, hesitate to adopt these recommendations and perceive that the use of fertilizers leads to "*addiction*". Different indicators are available to evaluate effectiveness of fertilizer application. We considered six different indicators: Agronomic Use Efficiency (AUE), Value-Cost-Ratio (VCR), Recovery Efficiency (RE), Capture Efficiency (CE), Soil Supply Capacity (SSC) and (partial) Nutrient Balances (NB). On-farm experiments were conducted for four years at 16 different locations. Crops involved were wheat, teff and hanfets. Experimental outcomes were evaluated using laboratory data on nitrogen, phosphorus and potassium (NPK) content of both soil and crops. Significant differences between the crops were found for CE, RE, NB and VCR. Wheat overall was found most extractive. Correlation between SSC and N-total and between RE and N-uptake was significant for all crops. For both nitrogen and phosphorus, NB correlated significantly with SSC for wheat and teff. Interaction between SSC, RE and NB demonstrated a significant trend for wheat: soils with higher SSC had lower NB and higher RE than soils with lower SSC. We concluded that achieving efficient use of mineral fertilizer goes at the cost of nutrient stock sustainability. The use of Integrated Soil Fertility Management-strategies is recommended to address these complex feedback

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and interaction mechanisms and to arrive at a sound balance between efficiency and sustainability of fertilizer use.

Keywords Sustainability · Resilience · Fertilizer use efficiency · Nutrient balances · Tigray

14.1 Introduction

In sub-Saharan Africa crop productivity is low and in many cases affecting food security and consequently livelihoods of rural communities. Many reasons are indicated for these low levels of crop yield, one of them being nutrient availability. The observation of systematic macro-level nutrient depletion (Stoorvogel et al. 1993; Sanchez and Swaminathan 2005) was the starting point for a series of initiatives to mitigate this depletion at site level (Jama and Pizarro 2008; Vanlauwe et al. 2010). A relatively simple and straightforward way to deal with depletion and to increase crop productivity is the application of mineral fertilizers. Sub-Saharan soils, however, are not always that responsive to fertilizer inputs. This lack of response often is attributed to depleted soils, probably also in combination with fixation of specific nutrients. Lack of response also might relate to a relatively high nutrient content of some soils; additional nutrients then are not required (Vanlauwe et al. 2011). In addition, factors like erratic rainfall or low levels of crop management interfere with successful response towards fertilizer application.

In Tigray, our study area, local extension bureaus recommend considerable quantities of mineral fertilizer to increase productivity. Farmers, however, frequently hesitate to adopt these recommendations due to various reasons, ranging from risk perception and high cost of fertilizer to an observed lack of response to fertilizer application (Kraaijvanger and Veldkamp 2015). Furthermore, a frequently heard statement of farmers in relation to the use of fertilizer is that it creates "*addiction*". In farmers' words: "*if mineral fertilizer was used one year, using it again in the next year will be needed to get acceptable produce*". Tittonell (2007) made a similar observation in Western Kenya. To these farmers it appears that applying fertilizers (as a curative action) results in a reduced capacity of the soil to supply nutrients. This observation strongly contrasts with the residual effect farmers normally observe in case of using traditional practices like applying manure or other organic fertilizers.

A wide range of indicators is available to evaluate the effectiveness of fertilizer application. Each indicator addresses a specific concern, mostly in relation to quantifying use efficiency or stock balance for specific nutrients. Agronomic Use Efficiency (AUE) deals with the increase in productivity as a result of the application of additional nutrients (Vanlauwe et al. 2011). It is an instrument to evaluate the agronomic efficiency of fertilizer use and to estimate optimal application rate. Value-cost ratio (VCR) is an indicator related to AUE and includes the costs (of fertilizer inputs) and revenues in order to estimate economic efficiency (Donovan et al. 1999).

Recovery Efficiency (RE) or Recovery Fraction relates to the fraction of applied nutrients that is returned in the harvested crop (Haefele et al. 2003; Chikowo et al. 2010) and is an example of a crop-based indicator. The amount of nutrients found in the harvested product compared to the total uptake is expressed in the so-called Capture Efficiency (CE), which is again a crop-based indicator addressing recovery (Chikowo et al. 2010). Partial and Full Nutrient Balance (NB) approaches (Stoorvogel et al. 1993; Haileslassie et al. 2005) go beyond fertilizer application and are used to estimate long-term changes in nutrient stocks.

Internal Nutrient Efficiency (INE) focuses on the quantity of grain that is produced compared to the uptake of nutrients in the above ground parts and is crop based (Haefele et al. 2003). Indigenous Nutrient Supply (INS) is defined as the uptake of a specific nutrient from (unfertilized) control plots, provided that other nutrients are not limiting (Haefele et al. 2003). Indigenous Nutrient Supply is an example of a soil-based indicator. Kurwakumire et al. (2014) used relationships based on soil properties like pH and Soil Organic Carbon (SOC) to estimate the value of INS for specific soils. Nutrient Uptake Efficiency is defined as the ratio of actual recovery and potential recovery in case all conditions are optimal, its scope essentially being agronomic, focusing on closing yield gaps (Janssen 1998).

Two related concepts are those of residual recovery and nutrient supply equivalents (Janssen 2011). Residual recovery quantifies the effect of application of fertilizer in the next growing season and is especially important in relation to phosphorus. Nutrient supply equivalents aim at a balanced supply of nutrients which is assumed to result in efficiency. Residual recovery is (soil) supply based, whereas supply equivalents stress the crop-physiological importance of more than one nutrient.

All above indicators underline that both resource use efficiency and sustainability are main concerns (van Noordwijk and Brussaard 2014). The attention given to various forms of efficiency is legitimate given the scarcity of resources and the ambition to feed the future world population. In the past, efficiency was merely explained in terms of maximum profit and productivity, resulting in high-input low-efficiency agriculture, which suited the motives of individual farmers. At present, simple demand-supply reasoning is no longer in all cases considered appropriate to address the challenges of the global community. In response to this, sustainability became more and more in vogue in the past 20 years. The nature of this sustainability is agronomic rather than environmental and is in relation to nutrients often connected to nutrient balances (De Jager et al. 2001). In the context of low-input farming the capacity of the soil to supply nutrients strongly relates to sustainability and is, for example, expressed in INS. In low-input high-efficiency agriculture (Koohafkan et al. 2012), soil nutrient buffers play a prominent role in supporting productivity and resilience of the involved agricultural systems.

Based on the outcomes of four years of on-farm experimentation in Tigray we explored the complex trade-offs and interactions between the concerns of efficiency, nutrient balances and soil supply capacity. To obtain a holistic picture we calculated six different indicators relating to resource use efficiency and nutrient stock for three main food crops in Tigray. Our focus was on nutrient supply capacity, which is a relatively new concept that links soil and crop and allows evaluations in time.

In addition, we commented on the "*addiction*" statement of the farmers and the remarkable sustainability of the traditional agricultural system in northern Ethiopia (Kraaijvanger and Veldkamp 2015).

14.2 Methods and Materials

14.2.1 Introduction

On-farm experiments were conducted in 16 different neighbourhoods for four consecutive years. In most cases, however, the actual location of an experimental site changed within these four years. In this chapter we included 37 experimental sites, considering only the first year of use as an experimentation site. The test crops were wheat, teff and hanfets. Hanfets is a traditional mixture of barley and wheat in variable ratios (Woldeamlak et al. 2001). In our research set up we challenged farmer groups to design their own experiments. In addition, we included replicated control treatments (unfertilized) and treatments with recommended fertilizer application of diammonium phosphate (DAP) and urea. Details are provided in Kraaijvanger and Veldkamp (2015). We used experimental outcomes in terms of yield, in combination with laboratory data on nitrogen, phosphorus and potassium (NPK) content of soil and crops to explore behaviour of soil and crops under fertilized and unfertilized conditions. In order to evaluate this behaviour we used six different indicators relating to uptake and source of nutrients used, with a focus on total uptake related to above ground biomass production (i.e., grain and straw). Nutrient uptake was calculated by multiplying crop produce with crop nutrient content.

All indicators considered were directly derived or slightly adapted from literature sources and defined as follows:

Agronomic Use Efficiency (AUE)
This indicator considers the effect of the applied fertilizer in terms of additional produce as compared to a control situation without nutrient inputs (Vanlauwe et al. 2011):

$$\mathrm{AUE} = (Y_\mathrm{t} - Y_\mathrm{c})/N_\mathrm{t} \tag{14.1}$$

Y_c=total dry matter produce control plots (kg/ha)
Y_t = total dry matter produce fertilized plots (kg/ha)
N_t = fertilizer nutrient input (kg/ha).

Soil Supply Capacity (SSC)
This indicator indicates the amount of nutrients that are supplied by the soil in case no fertilizer inputs are provided and represents the capacity of the soil to provide nutrients. SSC resembles Indigenous Nutrient Supply (INS), as was described by

Haefele et al. (2003). The difference is that INS presumes that the nutrient in question is limiting (and other nutrients are sufficient in supply). To estimate SSC, dry matter produce and crop nutrient content of the control plots were multiplied:

$$\text{SSC} = N_s = Y_c * f_c \tag{14.2}$$

N_s = soil nutrient supply (kg/ha)
f_c = nutrient content of produce control plots (fraction).

Recovery Efficiency (RE)
Resource Efficiency covers the efficiency of crops to use fertilizer resources. In this indicator uptake of nutrients of the above ground parts is compared to the input of fertilizer (Chikowo et al. 2010):

$$\text{RE} = (Y_t * f_t)/N_t \tag{14.3}$$

f_t = nutrient content of produce fertilized plots (fraction).

Capture Efficiency (CE)
Capture Efficiency relates the uptake of nutrients to the total supply of nutrients by inputs (of fertilizer) and by the soil (Chikowo et al. 2010). In our case supply is estimated by considering SSC and direct fertilizer inputs:

$$\text{CE} = Y_t * f_t/(N_t + N_s) \tag{14.4}$$

Partial Nutrient Balance (NB)
In a partial nutrient balance, output and input are compared to assess the possible risk for depletion (Haileslassie et al. 2005). In our case we considered nutrients contained in crop and straw:

$$\text{OUTPUT} - \text{INPUT} = \text{NB} = (Y_t * f_t) - N_t \tag{14.5}$$

Value-Cost-Ratio (VCR)
To calculate a Value-Cost-Ratio the value of the additional produce resulting from fertilizer application is compared to the cost of this applied fertilizer (Donovan et al. 1999). In our case we took as a cost for the applied fertilizer 2500 ETB for the recommended 200 kg. The revenue from 1 kg was estimated 5 ETB kg^{-1} for wheat and hanfets and 8 ETB kg^{-1} for teff (data for 2013; ETB = Ethiopian *birr*; 25 ETB = 1 US$):

$$\text{CR} = (Y_t - Y_c) * V_y/V_t \tag{14.6}$$

V_y = revenue produce (ETB/kg)
V_t = total cost fertilizer input (ETB).

14.2.2 Laboratory Analysis

For both fertilized and control plots, composite samples of the harvested parts (grains and straw) were analysed in the first experimentation year for total nitrogen (N), phosphorus (P) and potassium (K) content using wet destruction. In order to reduce costs, the number of laboratory analysis was restricted to three representative sites for wheat and hanfets and to two representative sites for teff. Averages for wheat, hanfets and teff were used to calculate the different indicators. Composite samples of the top soil (0–20 cm) of each experimental site were analysed for total N (Kjeldahl method), available P (Olsen method) and exchangeable K (ammonium-acetate extraction). Total N, available P and exchangeable K relate to medium term availability of respectively N, P and K.

14.2.3 Statistical Analysis

Means, standard deviations and coefficients of variation were calculated for both the yields observed in the specific sites and the outcomes of the crop analysis. Analysis of variance was used to evaluate differences between the crops for the specific indicators. In addition, correlations between specific variables were calculated. All statistics were conducted using MS-Excel.

14.3 Results and Discussion

Yields observed over the four experimentation years varied considerably and appeared to be site specific (Table 14.1). In general (grain) yields for wheat were highest. The application of recommended amounts of mineral fertilizers resulted in an increased nitrogen content for wheat, hanfets and teff (Table 14.2). With respect to phosphorus and potassium, differences between recommended application and controls were much less. In addition, straw contained a surprising high content of potassium in comparison to grains.

As expected, different crops responded differently with respect to nutrient uptake (Table 14.3). Wheat can be considered quite extractive; teff at the other hand is relatively mild in that respect. Differences between the crops were significant for the crop physiological indicators Recovery Efficiency (RE) and Capture Efficiency (CE) (for both N and P), for the environmental indicator Nutrient Balance (for both N and P) and for the economic indicator Value Cost Ratio (VCR). For the soil-based

Table 14.1 Average grain and straw production of fertilized and control plots for the sites involved (cv = coefficient of variation; n = number of plots)

			Control				Recommended fertilizer application (N and P)[a]			
Site	Year	Crop	Average grain (kg/ha)	Average straw (kg/ha)	cv grain (%)	n	Average grain (kg/ha)	Average straw (kg/ha)	cv grain (%)	n
Adigudat	2010	Wheat	1235	3127	19.8	6	1810	4663	2.2	3
Adigudat	2011	Wheat	1289	3988	14.6	2	2757	9360	13.5	4
Adigudat	2012	Wheat	975	1561	38.2	2	2588	3930		1
Adowro	2011	Wheat	1516	3571	18.9	3	3238	7245	16.8	3
Adowro	2013	Wheat	3439	4536	19	2	3549	5184		1
Awadu	2012	Wheat	874	1570	19.2	2	757	1587		1
Awadu	2013	Wheat	1712	2388	5.9	3	2478	2916		1
Biherawi	2011	Wheat	2137	4783	7.7	2	2139	6747	7.4	3
Biherawi	2013	Wheat	1381	1835	14.6	3	2709	3616		1
Dingelat	2010	Wheat	2077	2628	41.6	6	2348	2878	26.3	4
Dingelat	2013	Wheat	1053	1622	13.1	3	2322	3893	18.2	4
Endamariam	2010	Wheat	1105	1750	35.1	4	2010	3667	10.6	3
Gudowro	2010	Wheat	2397.5	3180	9.9	4	3720	5050	14.9	4
Gudowro	2012	Wheat	2307	3194	13.5	2	2906	3853	20.6	4
Machalawi	2010	Wheat	966	1766	15.2	5	1157	3090	17	6
Machalawi	2012	Wheat	1536	1973	13.2	3	1708	2651	16.1	2
Mayzagra	2011	Wheat	1956.2	4269	2.2	2	3061	6524	32.8	3
Mayzagra	2012	Wheat	2470.5	3658	45.2	2	2905	4179	13	2
Mayzagra	2013	Wheat	1157.3	1900	17.4	3	2243	3745	15.6	3
Mymisham	2011	Wheat	1350.9	2554	35.4	3	2936	7227	17.8	3

(continued)

Table 14.1 (continued)

			Control				Recommended fertilizer application (N and P)[a]			
Site	Year	Crop	Average grain (kg/ha)	Average straw (kg/ha)	cv grain (%)	n	Average grain (kg/ha)	Average straw (kg/ha)	cv grain (%)	n
Mymisham	2013	Wheat	1757.7	2235	24.9	3	3903	5063		1
Siluh	2010	Wheat	1676	2424	9.5	5	2260	4103	6	3
Siluh	2013	Wheat	935.7	1374	6.1	3	1759	3155	3.7	3
Tikuz	2013	Wheat	1111	2554	36.3	3	1554	5413		1
Zalaweni	2010	Wheat	1596.7	2127	33.2	3	1243	1908	5.4	4
Zalaweni	2013	Wheat	1046.3	1289	31.4	3	2135	2539		1
Adigudat	2013	Teff	1112	2883	2.1	3	405	2781	0	1
Munguda	2010	Teff	780	2843	14	4	1038	4588	9.3	3
Munguda	2011	Teff	805	2831	12.6	2	1079	6104	7.8	4
Adowro	2010	Hanfets	1314	2734	18.5	7	2040	4010	10.6	3
Awadu	2010	Hanfets	678	2193	10.5	4	910	3610	20.5	3
Biherawi	2010	Hanfets	1215	2423	17	4	1713	3973	2.8	3
Endamariam	2013	Hanfets	752	2421	31.2	3	949	4245		1
Machalawi	2013	Hanfets	1436	1854	16.5	3	2014	2553		1
Mymisham	2010	Hanfets	1150	3870	41.3	3	1730	5678	18.7	4
Zonghi	2010	Hanfets	1135	3518	32.8	4	1288	4510	12.8	4
Zonghi	2011	Hanfets	670	2168	36	2	1497	5250		1

[a]Recommended application for all sites was 61 kg N and 24 kg P except for the Awadu, Mayzagra, Siluh and Zalaweni sites (41 kg N and 24 kg P)

Table 14.2 Nutrient composition of grain and straw for different crops (cv = coefficient of variation)

		Control						Recommended fertilizer application (N and P)[a]					
Crop	n	Average N (g/kg)	cv N (%)	Average P (g/kg)	cv P (%)	Average K (g/kg)	cv K (%)	Average N (g/kg)	cv N (%)	Average P (g/kg)	cv P (%)	Average K (g/kg)	cv K (%)
Wheat (grain)	3	16.3	13	4.2	11	4.8	11	18.7	17	4	5	5	0
Wheat (straw)	3	3.1	20	1	37	16	6	3.6	17	1.1	42	19	9
Teff (grain)	2	15.5	7	4.1	3	5	0	16.4	3	4.2	9	5	0
Teff (straw)	2	5.2	3	1.2	22	8.3	14	4.9	12	1.1	47	8	35
Hanfets (grain)	3	17.9	15	4.3	8	5.7	10	19.3	15	4.6	6	5.7	10
Hanfets (straw)	3	4.6	29	1.6	39	15	18	5.1	42	1.7	48	14	14

[a]Recommended application for all sites was 61 kg N and 24 kg P except for the Awadu, Mayzagra, Siluh and Zalaweni sites (41 kg N and 24 kg P)

Table 14.3 Calculated average values for different indicators to evaluate the effect of fertilizer inputs

Indicator type	Indicator acronym (units)	Concern	Wheat	Teff	Hanfets
Agronomic use efficiency	AUE-N total (kg/kg)	Agronomic	45.6	23.7	33.9
	AUE-P total (kg/kg)	Agronomic	286.2	189.2	239.4
Soil supply capacity	SSC-N total (kg/ha)	Soil (properties)	33.8	23.0	30.3
	SSC-P total (kg/ha)	Soil (properties)	9.2	5.5	8.7
Recovery efficiency	RE- N total* (%)	Crop (physiology)	110.2	48.0	81.6
	RE-P total* (%)	Crop (physiology)	60.0	30.3	59.0
Capture efficiency	N-CE* (%)	Crop (physiology)	67.2	34.9	54.6
	P-CE* (%)	Crop (physiology)	43.0	23.3	43.2
(partial) Nutrient balance	NB-N* (kg/ha)	Environment	−4.5	33.3	11.0
	NB-P* (kg/ha)	Environment	9.6	16.7	9.8
Value to cost ratio	VCR*	Economic	2.1	0.6	1.0

*Significant difference between the crops ($p < 0.05$)

indicator Soil Supply Capacity (SSC) and for the agronomic indicator Agronomic Use Efficiency (AUE) differences between the crops were not significant. Differences in uptake efficiency are important in crop rotations. Continuous cultivation of wheat will result in much more depletion than rotations including the sequence wheat-hanfets-teff. In such rotations wheat is the fertilized component and able to capture the nutrients supplied. Fertilizing teff doesn't seem to make much sense as recoveries can be below 50% (Table 14.3). In addition, teff in many cases might start lodging when it is fertilized too much. In traditional (unfertilized) rotations, teff often is followed by legumes to obtain a soil enriched with N for the next (wheat) crop.

SSC-N significantly correlated with total N, but SSC-P was not significantly related to available P (Figs. 14.1 and 14.2). Although both total N and available P are related to medium term availability, soil supply of P was not all determined by available P, while supply of N indeed related to total N. In the context of our case study (low-input systems with traditional management), N-uptake (under non-fertilized conditions) primarily depended on mineralization of organic N, which is a main factor determining total N. P-supply likely interacted with adsorption and fixation by different soil components and with the low solubility of P in the soil solution. In addition, P-supply in the context of Tigray will be limited by the short growing period (about 100 days). This resulted in P-uptake being almost independent of available P.

For the fertilized plots, significant positive relationships for both N and P were found between supply capacity of the soil and recovery of mineral fertilizer by the crop (Figs. 14.3 and 14.4). This indicated that nutrient recovery increased and the fertilizer supplied was used more efficiently. In the case of wheat, N-recovery of above 100% required a Soil Supply Capacity of about half of the total input of N

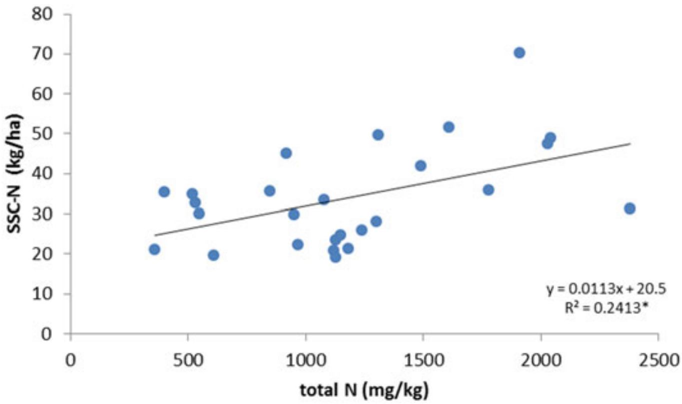

Fig. 14.1 Soil supply capacity (SSC) for N versus N-total for wheat (*indicates significant at $p = 0.05$)

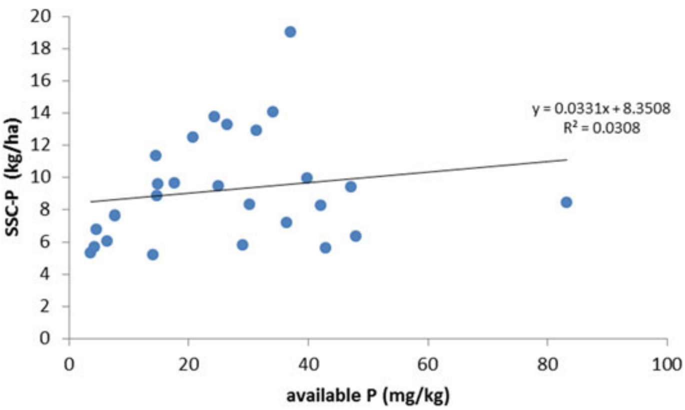

Fig. 14.2 Soil supply capacity (SSC) for P versus P-available for wheat

through fertilizer. The recovery for P increased and correlated with soil supply but never resulted in a recovery above 100%; P-applied consequently was not used fully. Low soil supply capacities apparently related to a higher probability for P-fixation; P being adsorbed rather than being used by the crop.

For wheat significant relationships were found between crop uptake and supply capacity of the soil (Fig. 14.5) and uptake above application level (41 and 64 kg/ha) in most cases was substantial. This indicated that the impact of soil supply on total uptake is important. Within our range of observations, contributions from the soil sometimes even exceeded fertilizer inputs.

For wheat and teff, partial nutrient balances (for N) demonstrated a significant negative relationship with Soil Supply Capacity (Fig. 14.6). For wheat, a higher soil supply resulted overall in negative balances: the presence of more easily available

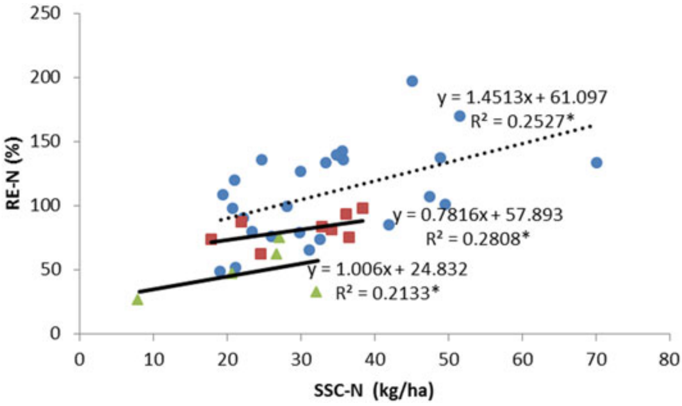

Fig. 14.3 Recovery efficiency (RE) versus soil supply capacity (SSC) for nitrogen for three grain crops (circles = wheat; squares = hanfets; triangles = teff; * = significant at $p = 0.05$)

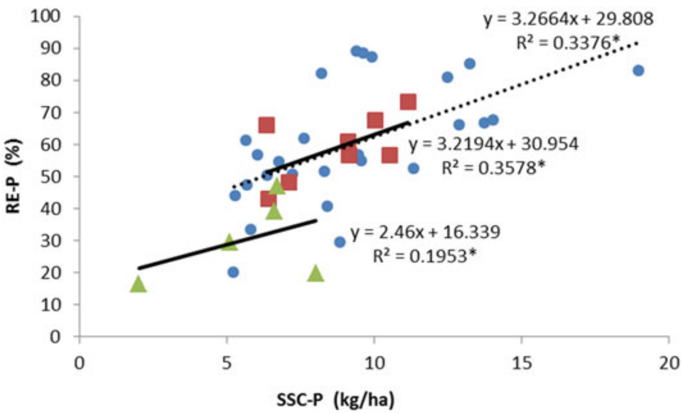

Fig. 14.4 Recovery efficiency (RE) versus soil supply capacity (SSC) for phosphorus for three grain crops (circles = wheat; squares = hanfets; triangles = teff; * = significant at $p = 0.05$)

nutrients in the soil, in combination with fertilizer input, apparently led to a higher level of extraction. This stronger extraction might be related with the promotion of root development and decomposition of organic matter by fertilizer inputs. In about half of the cases, nutrient balances were negative for wheat, despite the use of fertilizers. Wheat, as mentioned before, had a strong ability to extract nutrients. For both hanfets and teff, (partial) nutrient balances did not become negative within the range observed. These crops clearly were much less extractive.

Plotting partial nutrient balances and resource use efficiency (in terms of RE) for N and P resulted in two observations (Figs. 14.7 and 14.8):

(1) Higher Supply Capacities resulted in lower nutrient balances and higher resource use efficiencies. Different ranges of Soil Supply Capacity (for both N and P)

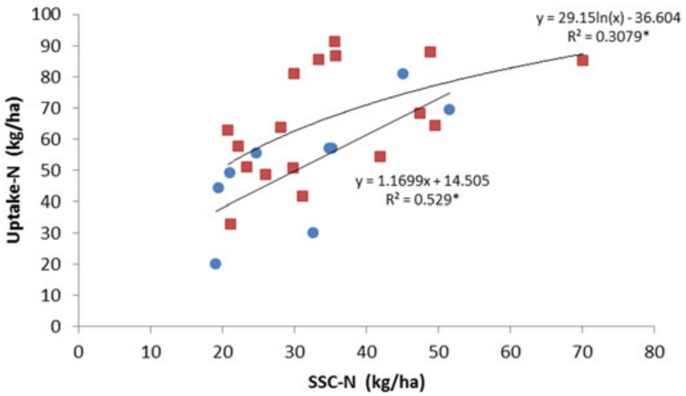

Fig. 14.5 Uptake of nitrogen versus soil supply capacity (SSC) for two different nitrogen input levels (circles = 41 kg N/ha; squares = 64 kg N/ha; * = significant at $p = 0.05$)

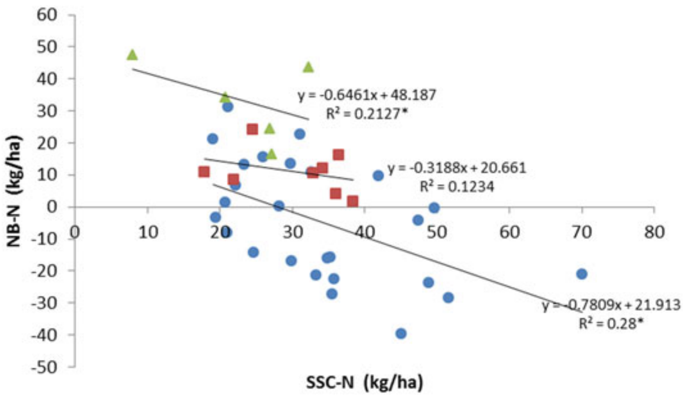

Fig. 14.6 Partial nutrient balances (NB) versus soil supply capacity (SSC) for nitrogen for different crops (circles = wheat; squares = hanfets; triangles = teff; * = significant at $p = 0.05$)

resulted in significantly different outcomes for nutrient balances and resource use efficiency. Consequently, soils with a high Soil Supply Capacity tended to deplete, even when recommended quantities of fertilizer were applied.

(2) Recovery Efficiency (RE) and (partial) Nitrogen Balance (NB) demonstrated a strong linear correlation. This correlation, however, related to the way RE and NB were calculated and the use of only two input levels for N and only one input level in the case of P. The strong intrinsic relation between both indicators is also demonstrated by the observation that in the case of N, a recovery of over 100% (automatically) resulted in a negative balance.

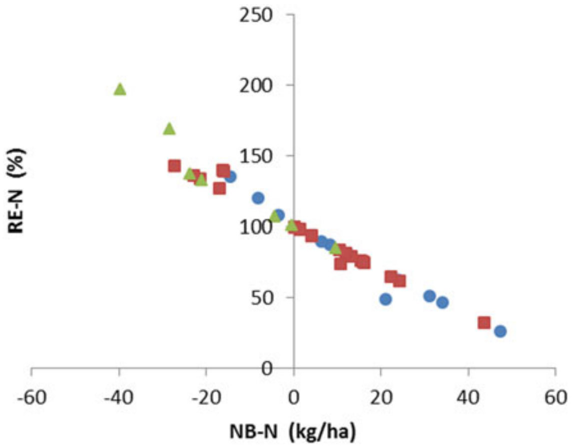

Fig. 14.7 Partial nutrient balances (NB) versus Recovery efficiency (RE) for nitrogen (wheat). ANOVA-difference between different ranges of SSC-N is significant at $p = 0.05$. (circles = SSC-N < 30 kg/ha; squares = SSC-N between 30 and 40 kg/ha; triangles = SSC-N > 40 kg/ha)

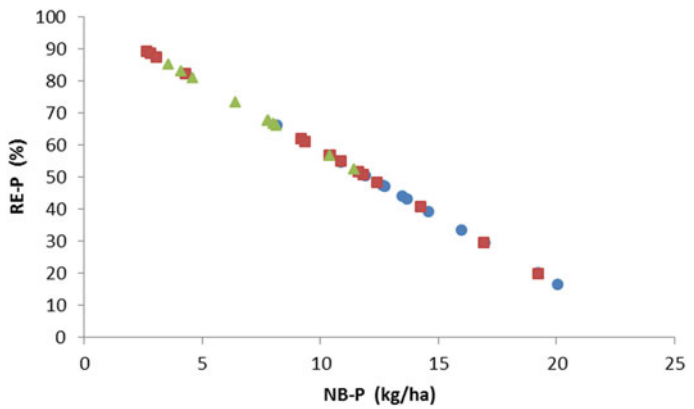

Fig. 14.8 Partial Nutrient balances (NB) versus recovery Efficiency (RE) for phosphorus. ANOVA-difference between different ranges of SSC-P is significant at $p = 0.05$. (circles = SSC-P < 7.5 kg/ha; squares = SSC-P between 7.5 and 10 kg/ha; triangles = SSC-P > 10 kg/ha)

14.4 Synthesis

Using different indicators to evaluate resource use efficiency and stock balances of fertilizer application in Tigray demonstrated that differences between the crops involved were significant and mainly related to different extractive capacities. As a consequence, the use of such indicators in a comparative way at scale levels above the field/crop scale level does not make much sense.

Farmers in Tigray make use of such crop specific differences. In their traditional rotations, wheat is the fertilized crop and is followed by crops like hanfets and teff. Our outcomes made clear that wheat was the most extractive crop followed by respectively hanfets and teff. As a consequence, the long-term sustainability of agricultural systems in Tigray can be explained by the traditional use of such rotations in combination with legumes, the use of crop residues and the practice of fallowing (Kraaijvanger and Veldkamp 2015).

Long-term sustainability of fertilizer application can be expressed by using nutrient balances; resource use efficiency of fertilizer application is a relatively short-term concern; relationships of Soil Supply Capacity (SSC) with both efficiency and nutrient-stock indicators were significant. Consequently, SSC appears a useful indicator in addition to the existing ones: (1) it combines short-term crop aspects (extraction) and long-term soil aspects (capacity); and (2) it allows the inclusion of a soil based temporal dimension for the evaluation of agricultural systems.

The observation of farmers in Tigray that the use of (mineral) fertilizers results in "*addiction*" was supported by our evaluation based on nutrient balances, resource use efficiency and soil supply capacity. The outcomes of the calculated (partial) nutrient balances demonstrated that, despite application of fertilizers, nutrient balances were in many cases negative, especially in the more fertile soils that were able to supply additional nutrients. As a consequence, SSC will be reduced and the system moves to a state with lower efficiency and less depletion. This (system) feedback will consequently reduce excessive extraction of nutrients. Apparently a trade-off existed between efficiency (aiming at crop supply) and stock supply. It is likely that these feedbacks were also responsible for supporting sustainable land use in Tigray for over 2500 years despite calculated negative nutrient balances at the higher scale levels (Kraaijvanger and Veldkamp 2015).

At first sight, applying fertilizers appears to reduce system losses, however, the common assumption that applying fertilizers in all cases will have beneficial effects does not hold. Soil stock supply, resource use efficiency and nutrient balances are clearly interconnected and cannot be separated. The only way to minimize the effect of these trade-offs is to re-use as much as possible crop residues and manure on top of the application of (mineral) fertilizers. Integrated Soil Fertility Management (ISFM) strategies (Vanlauwe et al. 2010) embraces such practices and is in this way able to address concerns of both resource use efficiency and nutrient stock sustainability. ISFM therefore entails a more feasible option to improve crop yield than the sole (and costly) input of mineral fertilizer. Still, development of systems fully sustainable with respect to nutrient balance remains difficult (Harris 1998). In addition to the reduction of NPK-stocks (Tittonell 2007), it is also possible that fertilizer inputs resulted in increased mining of trace elements. The absence of these essential nutrients then might lead to an additional loss of productivity and definitely requires further research.

14.5 Conclusion

Achieving efficient use of fertilizer will be at the cost of nutrient stock sustainability. In most literature the focus is merely on agronomic and crop performance, whereas soil continues to remain a *"black box"* that is to be filled with nutrients (i.e., mineral fertilizer inputs) in order to supply the nutrients required. However, the situation in reality is much more complex. Soils are not static *"black boxes"*, but interact with nutrient use efficiency and stock sustainability. At the same time, dynamic trade-offs exist between stock sustainability and fertilizer use efficiency. As a consequence, Soil Supply Capacity changes and crop production systems move back and forth from more to less fertile states. The presence of such complex feedbacks requires ISFM strategies to arrive at a sound balance between efficiency and sustainability of fertilizer use. Within the context of Tigray, these feedbacks were witnessed by the frequently heard statement that the use of fertilizers leads to "*addiction*", as well as by the long-term sustainability of traditional farming systems.

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