Bridging attainable yield potentials of potato (*Solanum tuberosum L.*) through nitrogen and phosphorus nutrients management in northwestern Ethiopia

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Abstract

(Solanum tuberosum L.)

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Keywords: Farta, Laigaint, Soil fertility, Tuber yield, Yilmana Densa

Introduction

Potato (*Solanum tuberosum L.*) is one of the dominant crops globally that ranks fourth in terms of volume of production and its area coverage (FAOSTAT, 2007). It ranks first among root and tuber crops in Ethiopia (CSA, 2016). Potato is characterized as a cheap and nutritive food security crop. Because of its high yield with good nutritive values per unit area and per unit of time than other major cereal crops (Kanter and Elkin, 2019; Beals, 2019), it is considered as a food and nutrition security crop. Potato is one of the strategic crops to the United Nation's Millennium Development Goals of achieving food security and poverty eradication and 2008 was recognized as the year of potato by the United Nations. Its contribution to food security with a stable price might be continued as the price of potatoes mainly depends on local demand and supply than the global market. A short production cycle and early maturing habits are additional benefits of potato to intensification than many other crops.

Ethiopia has an immense potential to boost the productivity of potato (*Solanum tuberosum L.*) especially in the highlands (Woldegiorgis *et al.*, 2012; Haverkot *et al.*, 2012). About 70% of the cultivated land of Ethiopia is suitable for potato production (FAOSTAT, 2008) but only 2% of the potential has been used (Hirpa *et al.*, 2012). About 40% of potato producers are concentrated in the northwestern parts of Ethiopia: South Gonder, North Gonder, East Gojam, West Gojam, and Agew Awi administrative zones, the Amhara National Regional State of Ethiopia (Hirpa *et al*., 2012) that could be related to agroecological suitability. These areas are characterized by a high density of demography with less food and nutrition security that needs improving and promoting high yielding crops and potato is highly recommended under such situations (De Jong, 2016). The Ethiopian Agricultural research system placed its national potato research coordination at Adet Agricultural Research Center (West Gojjam) to use the existing potential of the region through research interventions and promotion. The current state of potato productivity in Ethiopia is less than 10 t ha^{-1} (Deresseh et al., 2016; Hassen *et al*., 2015, Haverkort *et al*., 2012, Hirpa *et al*., 2015) and its total annual production is only about 0.5 million tons.

On the other hand, Haverkot et al., (2012) reported the highest yield report of potato (64 t ha^{-1}) around Shashemene in Ethiopia that indicates high variability of productivity in the country governed by different biotic and non-biotic factors. Ethiopia soil has been depleted because of negative input to out-put balances of the nutrients (low soil fertility) that could contribute to the high variability and low crop productivity including potato (Amare, *et al*., 2018, Amare *et al.*, 2013, Hirpa *et al*., 2012; Kebede and Ketema, 2017; Muleta and Aga, 2019). Among plant nutrients, nitrogen and phosphorus are so far the most yield-limiting nutrients (Amare *et al*., 2018) while Muleta and Aga (2019) reviewed that nitrogen is the most yield-limiting nutrient of potato. However, finding and updating on the biological and economical response of potato to nitrogen and phosphorus is a critical gap in northwestern Ethiopia. Therefore, this research was conducted to get the biological and financial optimum rates of nitrogen and phosphorus potato production in Northwestern Ethiopia.

Materials and Methods

Study sites

Yilmana Densa town is located at about 42 km from Bahir Dar on the way to Addis Ababa through Mota and represents potato growing areas of west Gojjam, Agew Awi, and East Gojjam zones. The district is characterized by highland and midlands. It has a unimodal rainfall with a mean of 1240 mm yr^{-1}. June, July, and August receive the largest shares of the annual rainfall. It has 9.3^{O}C and 25.7^{O}C, minimum and maximum temperatures respectively. The local geology is volcanic basalt and Cenozoic pyroclastic fall deposits (Zewde, 2009). Potato and food barley are the most important crops in the highlands of the district. The district is one of the highly populated districts of the region that led to very small farmland per capita. Farta and Lai Gaint are parts of the south Gondar Admiration zone of the Amhara National Regional State with similar rainfall patterns to Yilmana Densa. Potato and food barley are also the dominant cultivated crops in these districts. The farming system of the study sites is subsistence and crop-livestock mixed type. Potato productivity in Ethiopia and annual production of potato at the global level is displayed in Figure 1 and 2, respectively.

Treatment setup

The experiment was conducted for three years in the rainy season with three sites per location per year (3 for Yilmana Densa and 3 for Farta & Laigaint). A factorial experiment with four levels of nitrogen (46, 92, 138, 194 kg N ha^{-1}) combined with three levels of phosphorus (46, 69, 92 P_2O_5 kg ha^{-1}) was used for the study. One treatment with no nutrient input (control) was also included as a pilot to assess the current state of potato production without fertilizer application as there are potato growers without fertilizer. Treatments were replicated three times and arranged in a randomized complete block design (RCBD). Nitrogen was applied by three splitting: one third at planting, one-third three weeks after germination, and the final one-third at flowering while the whole dose of phosphorus was applied at planting. Urea (46% N) and TSP (46% P_2O_5) were sources of fertilizers for nitrogen and phosphorus respectively. Gudene is an improved potato variety developed by the Ethiopian research system and a well-known recommended variety in the study areas and hence used for the study. The distance between plants and rows was 0.3m and 0.75m respectively. The gross size of each plot was 13.5m^2 (3m*4.5m) while the data was collected from the central 4 rows with a plot size of 9m^2 (3m*3m). Earthing up was uniformly done at the ages of 3 weeks after germination. Redomil at the rate of 3 kg ha^{-1} was applied uniformly for the control of late blight disease.

Soil sampling and analysis

Composite soil samples were collected at the depth of 0-20 cm before planting from each site. Collected soil samples were air-dried and ground by mortar and pestle. Soil pH was determined in a 1:2.5 soil to water suspension following the procedure outlined by Sertsu and Bekele (2000). Soil organic carbon content was determined by the wet digestion method using the Walkley and Black procedure (Nelson and Sommers, 1982). Total nitrogen was determined using the Kjeldahl method (Bremner and Mulvaney, 1982) while the available phosphorus was determined following the Olsen procedure (Olsen and Sommer, 1982). The exchangeable potassium was measured by flame photometer after extraction of the samples with 1N ammonium acetate at pH-7 following the procedures described by Sertsu and Bekele (2000).

Data analysis

The effect of independent variables (nitrogen, phosphorus, and their interaction) on the dependent variable (potato tuber yield) was statistically tested. The analysis was made for each site and year and combined as well. Analysis of variance (ANOVA) was carried out to assess the difference between treatments. Upon the existence of significant difference for ANOVA, ($p < 0.05$), further analysis of mean separation was carried out using Duncan's Multiple Range Test (DMRT). Graphical analyses were also employed to evaluate response curves over different doses of nitrogen and phosphorus nutrients. The partial budget analyses were done based on (CIMMYT, 1988). The cost of NPS and urea was 1284.05 and 1158.58 Birr per 100 kg; respectively. The farm gate price of potato (Birr 100 kg^{-1}) was 487 at Yilmana Densa and 450 Birr at Laigaint and Farta.

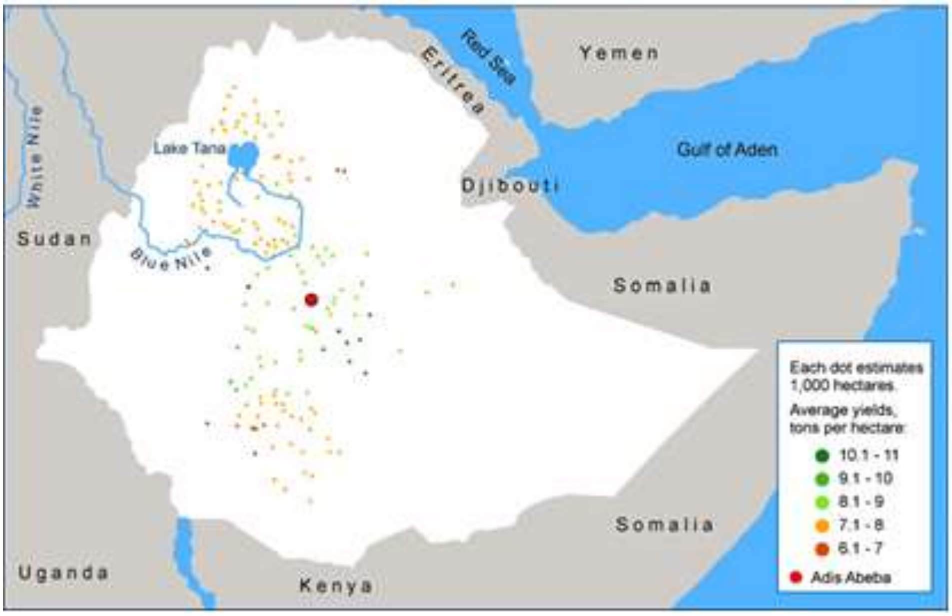

Figure 1. Potato productivity in Ethiopia: earch.). Accessed on 8/1/2019

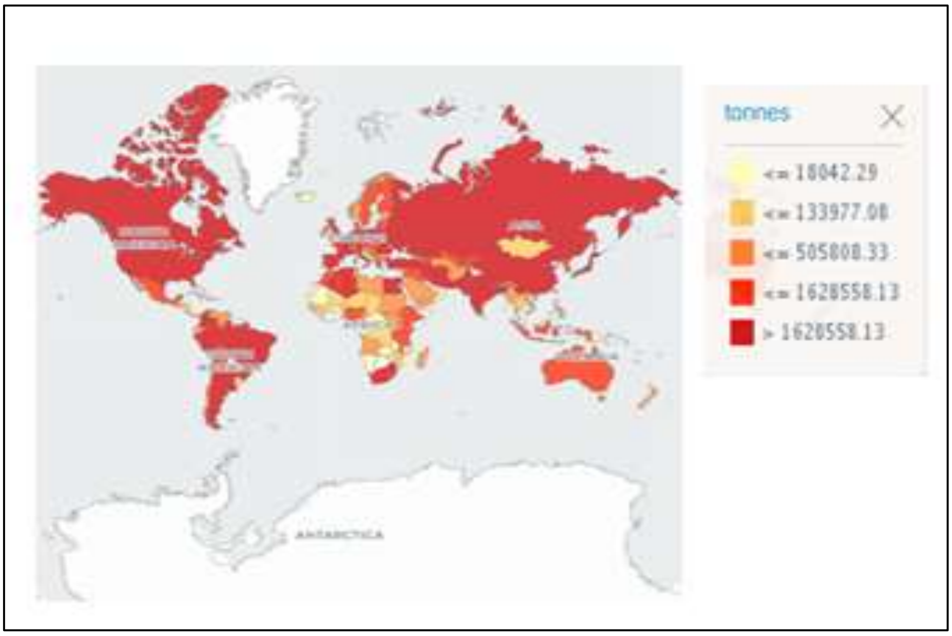

Figure 2. Annual production of potato at the global level. http://www.fao.org/faostat/en/#data/QC/visualize (average potato yield from 1994-2017). Accessed on 28/10/2020

Results and Discussion

Soil properties of the study sites

The pH of the soil (pH of water) was above five that ranged from 5 to 5.3 for the case of Yilmana Densa while for the South Gonder it was ranged from 5.1 to 5.4 both sites are moderately acidic (FAO, 1984). Soil acidity is not a critical yield-limiting factor for the study sites especially in the upper parts of the landscapes as Andosol is dominating in that parts of the districts with pH higher than our report here. Moreover, potato is tolerant of acid soils compared to other sensitive crops and hence pH was not a limiting factor for our research. The soil organic carbon (SOC) contents of the study sites ranged from 0.96 to 1.75% for Yimana Densa and 1.14 to 2.01% for south Gondar. Accordingly, the soils of Yilmana Densa were below the critical limits and south Gondar ranges from below to critical levels (Loveland and Webb, 2003; Murphy, 2014). Generally, soils of the study areas were low in SOC that limits nutrients supplies including N and P (Murphy, 2014). Therefore, for optimum production of potato nutrients must be supplied in the forms of synthetic fertilizer, organic fertilizer, or in the form of synthetic integrated with organic fertilizers. The exchangeable potassium of the soil was ranged from 0.69 to 0.88 cent mol kg^{-1} of the soil for Yilmana Densa while for South Gondar it ranged from 0.46 to 0.62 cent mol kg^{-1} of the soil. The result of soil analysis on soil potassium was above the critical limits for all the study sites (IPI, 2016), indicating that potassium is not a priority fertilizer for the production of annual crops including potato with its current state as supported with the finding of other annual crops (Amare *et al*., 2018). The available phosphorus of Yilmana Densa was in a range of 9 to 10 ppm that is below the critical levels (Huygens and Saveyn, 2018) while for south Gondar it was highly variable (ranged from 10 to 20 ppm).

Yield response

The response of potato to the application of nutrients (NP) was higher as shown in Figure 3. The response to nitrogen was higher than phosphorus (Figure 3, Tables 1 and 2). Figure 3 showed that there was an increase in the yield of potato for the application of nitrogen even at the rates of 194 kg N ha^{-1}for all sites and for all seasons (Figure 3: A and B). The yield gap between the rates of nitrogen was higher and uniformly increased for nitrogen than phosphorus. However, the yield response to the applied phosphorus was not as strong as the response to nitrogen (Figure 3: C and D). The higher yield gap for the application of phosphorus was observed between the control (no fertilizer) and the treatments with phosphorus (Figure 3: C and D) compared to the response to nitrogen (Figure 3: A and B). For the applied phosphorus the yield was increased with a low slope coefficient.

The Analysis of variance (ANOVA) results of the research showed a significant yield difference ($p < 5\%$) for all sites and years to nitrogen (Table 1 and 2). The maximum tuber yield (40 t ha^{-1}) of potato was found in Yilmana Densa at a site called Chinkulit in the 2018/2019 cropping season using 194 kg of N ha^{-1}compared to 11 t ha^{-1} of tuber yield from control for the same location in the same year (data is not shown here). The average maximum yield of potato for the three years in Yilmana Densa for nitrogen was 29.2 t ha^{-1} by applying 194 kg of N ha^{-1} compared to 8.8 t ha^{-1}tuber yields from treatments without nutrient (Table 1). While the maximum potato tuber yield (297.5 t ha^{-1}) in south Gondar was recorded at a site called Tsegur Kidanimiret, in Farta district by applying 194 kg N ha^{-1}compared to 11.6 t $ha^{-1}$of potato tuber yield without nutrient input from the same site in the same season (2018/19), (data not shown). The three-year average tuber yield of potato in south Gondar was ranged from 7.54 t ha^{-1} to 22.08 t ha^{-1}without nutrient input and applying 194 kg N ha^{-1}; respectively (Table 2).

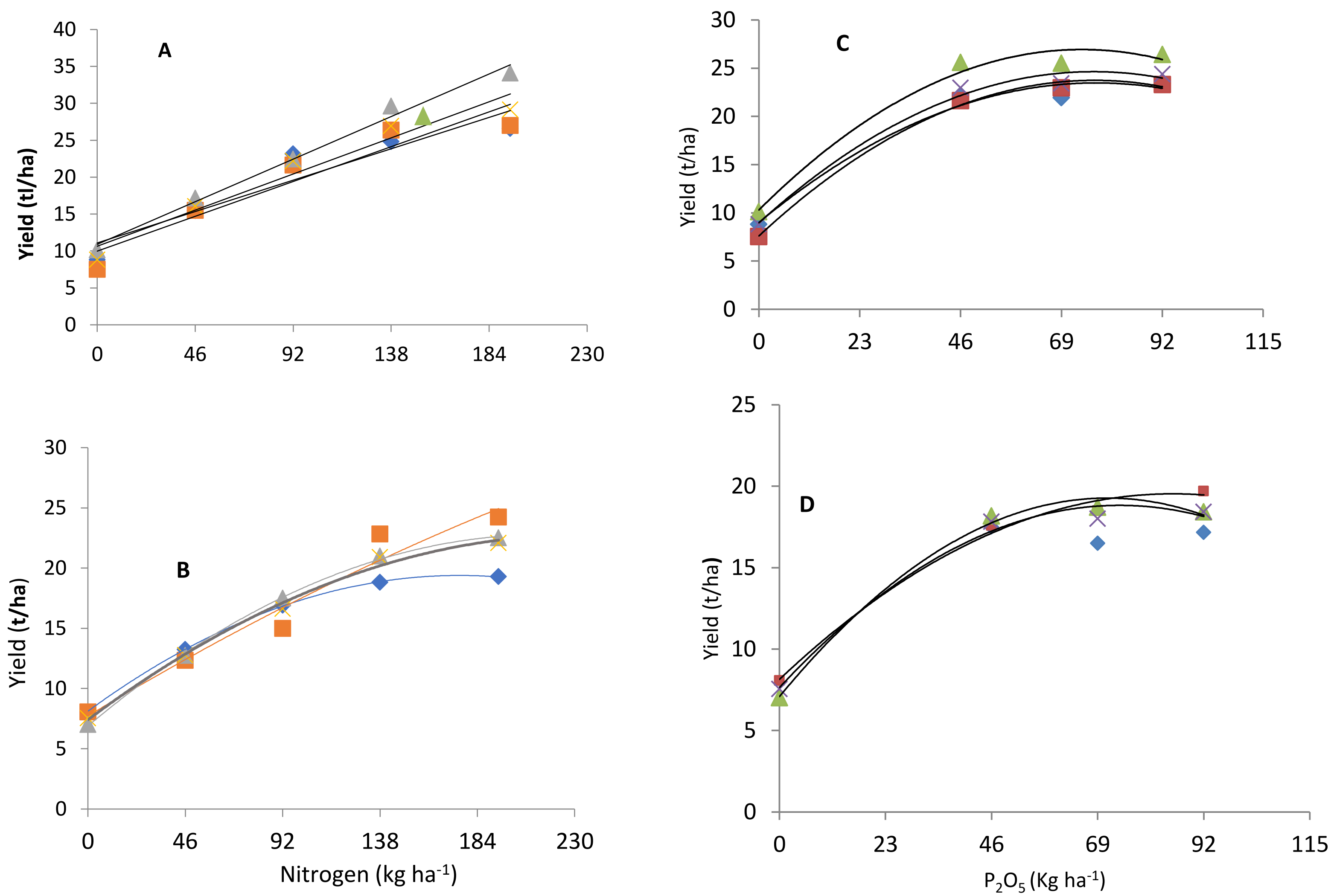

Figure 3. Response of potato to N (A Yilmana Densa and B South Gondar) & P (C Yilmana Densa and D south Gondar). Where: is year one is year two is year three and is the mean

Table 1. Potato response to applied NP at Yilmana Densa (tuber yield t ha^{-1}) over the years

Nitrogen (kg/ha)	Year 1	Year 2	Year 3	Mean
46	15.48	15.52	17.18	16.06
92	23.16	21.64	22.46	22.21
138	24.81	26.37	29.61	26.93
194	26.61	27.01	34.11	29.16
LSD (0.05)	2.97	2.3	3.18	1.7
Phosphorus (P_2O_5 Kgha^{-1})				
46	22.17	21.63	25.61	22.98
69	21.94	22.97	25.51	23.41
92	23.43	23.31	26.41	24.38
LSD (0.05)	NS	NS	NS	NS
CV (%)	24.4	18.8	22.8	23
N*P	NS	NS	NS	NS
Control (0N and 0P)	-	7.53	10.13	8.83

Table 2. Potato response to applied NP at South Gondar (tuber yield t ha^{-1}) over the years

Nitrogen (Kg ha^{-1})	Year 1	Year 2	Year 3	Mean
46	13.23	12.33	12.74	12.76
92	16.91	14.99	17.50	16.61
138	18.81	22.82	21.00	20.89
194	19.28	24.23	22.51	22.08
LSD (0.05)	4.30	2.55	3.11	1.97
P_2O_5 (Kgha^{-1})				
46	17.50	17.59	18.17	17.82
69	16.50	18.49	18.71	18.01
92	17.17	19.70	18.43	18.43
LSD (0.05)	NS	NS	NS	NS
CV(%)	36.3	20.9	33	31
N*P	NS	NS	NS	NS
Control (0N and 0P)	-	8.06	7.01	7.54

The response of tuber yield to phosphorus was much less than to the responses for nitrogen for all the sites; resulting in a non-significant yield difference between phosphorus rates (Table 1 and 2). The smallest rates of phosphorus (46 kg P_2O_5 ha^{-1}) resulted in comparable tuber yield of potato as that of the maximum rates (69 and 92 kg P_2O_5 ha^{-1}) for all the sites and more specifically to south Gondar.

Our finding on nitrogen was in line with the findings of Esmael (2017) and Getie *et al.*, (2015) who recommended 110 kg N ha^{-1} for the major potato producing areas of Ethiopia although their recommendation was much lower than our finding. However, Esmael (2017) recommendation of phosphorus for the production of potato for the major producing areas of the country (90 kg P_2O_5 ha^{-1}) disagreed with our findings. He recommenced a higher rate that was two times our findings. The findings of Nyiraneza *et al*. (2017) in Canada showed no response to phosphorus application under different soils with different levels of soil phosphorus. They reported the recommended amount of N was 150 kg ha^{-1}. Similarly, Setu and Mitiku (2018) reported no response of potato to phosphorus in western Ethiopia. Alemayehu and Jember (2018) under the Koga irrigation scheme reached conclusions of different rates of phosphorus recommendations for different sites and varieties. They recommended 102 kg P_2O_5 $ha^{-1}$for variety Belete under low phosphorus conditions and for Gudene 69 kg P_2O_5 ha^{-1}. For areas with sufficient phosphorus, they recommended 69 kg P_2O_5 ha^{-1} for Belete and 52 P_2O_5 ha^{-1} for Gudene. However, our main difference with their finding was the growing season that is our experiment was in the main season while their experiment was entirely dependent on irrigation. Besides, the authors (Alemayehu and Jember, 2018) reached conclusions with only two sites experiment for a single irrigation season while our data was sufficient to capture the three rainy seasons. They claimed more than 30 ppm of available phosphorus (Olsen p) at Koga that might be less likely under the p limited farming systems of Koga and from our experiences. On the other hand, the recommendations by Hassen *et al*., (2015) was somewhat in line with our finding with phosphorus they recommended 69 kg $P_2O_5ha^{-1}$ while their recommendation to nitrogen was much lower than our finding as they recommended 80.80 kg N ha-1for the potato growing areas of northwestern Amhara Region (South Gondar and Gojjam areas). The recommendation of nitrogen made by Ayichew *et al.*, (2009) to the Vertisols of Debre Birhan area (138 kg N ha^{-1}) was in line with our findings to all sites of our study. They recommended 20 kg P_2O_5 ha^{-1}; lower than by half to our findings. Despite the arguments and suggestions of Fixen and Bruulsema (2014) as well as Follain *et al*., (2009) about higher requirements of phosphorus compared to other crops depending on the nature of the root system of potato, our result showed p satisfaction at lower P rates. The application of high rates of phosphorus without any significant biological yield could not only economically unjustifiable but also has an environmental risk (Ruark *et al*., 2014).

In Thailand, for the commercial production of potatoes, the rate of nitrogen and phosphorus (P_2O_5) reaches 187.5 Kg ha^{-1} and 187.5 Kg ha^{-1}, respectively (Kittipadakul *et al*., 2016) that implies the elasticity of potato response especially to phosphorus is very high. Khakbazan *et al*. (2019) also used the rates of nitrogen and phosphorus (138-151 N and 69-75 kg P_2O_5 ha^{-1}) similar to our findings and recommendations. The finding showed that the yield of potato at Yilmana Densa could be improved by more than threefold (greater than 300%) and at south Gondar by more than two and a half folds (greater than 250%) through nutrient applications (N) and its implication on food and nutritional security is tremendous as the study represents 40% of the potato producers of the country (Hirpa *et al*., 2012). There is a growing demand for potatoes for local consumption. One of the strategies to boost the production and productivity of potatoes in the potato farming systems of Ethiopia is through nutrient management (Hirpa *et al.*, 2012; Kebede and Ketema, 2017; Muleta and Aga, 2019).

Partial budget analysis

The partial budget analysis was employed to identify the economical optimum rates of NP fertilizer for the production of potatoes. Farm gate prices for potatoes were 4.87 and 4.50 Birr kg^{-1} of potato for Yilmana Dens and south Gondar; respectively. The cost of fertilizer was 1284.05 and 1158.58 for NPS and Urea; respectively. The significant difference in the biological yield was reflected in the economical responses of the partial budget analysis. Some of the treatments with N/P_2O_5 kg ha^{-1} (46/69, 46/92, 92/69, 194/46 at Yilmana Densa and 46/69, 46/92, 92/92, 138/69, 138/92, and 194/46 at south Gondar) were dominated and discarded from the analysis.

Accordingly, the highest marginal rate of return (70.9 Birr/Birr) for Yilmana Densa was found at the rates of 138 kg N ha^{-1} and 46 Kg P_2O_5 ha^{-1} (Table 3). For south Gondar, the maximum marginal rate of return (24.3 Birr/Birr) was found with treatments 138 kg N ha^{-1} and 46 Kg P_2O_5 ha^{-1} (Table 4). The optimum rate of NP fertilizers for potato production with this research disagreed with the one recommended by Yassin (2017). With the yield data of this research, the economic optimum rate could be continuously updated with the situation of farm gate price of potato and the cost of fertilizer. Based on the findings of this research, for Yilmana Densa and similar areas 138 kg N ha-1 and 46 Kg P2O5 ha^{-1} is recommended as the first option and 138 kg N ha^{-1} and 69 Kg P2O5 ha^{-1} as the second option while for south Gondar 138 kg N ha^{-1} and 46 Kg P2O5 ha^{-1} is profitable rate. Of course, the economic situations of farmers limit to use of the optimal amounts of fertilizer recommended by research (Gebru et al., 2017; Muleta and Aga, 2019). Alemayehu et al. (2020) found a very good marginal rate of return using 13.5 t ha^{-1} combined with 245.1 kg NPS ha^{-1}. Their finding is not in line with our finding as they recommend high rates of phosphorus than nitrogen. Moreover, it is hard to apply 13.5 t ha^{-1} s.

Table 3. Partial budget analysis for Yilmana Densa

Treatment	NPS (Kgha^{-1})	Urea (kgha^{-1})	Cost of NPS (Birr)	Cost of Urea (Birr)	TC (Birr)	Yield (ton)	TR (Birr)	MC (Birr	MR (Birr)	MRR (Birr/Birr)
0/0	0	0	0	0	0	8.83	43002.1	-	-	-
46/46	121.0	50	1553.7	579.3	2133.0	16.84	82010.8	2133.0	36875.7	17.3
92/46	121.0	150	1553.7	1737.9	3291.6	22.34	108795.8	1158.6	25626.4	22.1
92/92	242.0	100	3107.4	1158.6	4266.0	23.15	112740.5	974.4	2970.3	3.0
138/46	121.0	250	1553.7	2896.5	4450.2	25.87	125986.9	184.2	13062.2	70.9
138/69	181.6	225	2331.8	2606.8	4938.6	27.04	131684.8	488.5	5209.4	10.7
138/92	242.0	200	3107.4	2317.2	5424.6	27.87	135726.9	485.9	3556.2	7.3
194/69	181.6	346.7	2331.8	4016.8	6348.6	29.66	144444.2	924.1	7793.2	8.4
194/92	242.0	321.7	3107.4	3727.2	6834.6	30.59	148973.3	485.9	4043.2	8.3

Table 4. Partial budget analysis for South Gondar

Treatment	NPS (Kg)	Urea (Kg)	Cost of NPS (Birr)	Cost of Urea (Birr)	TC (Birr)	Yield (ton)	TR (Birr)	MC (Birr)	MR (Birr)	MRR (Birr/Birr)
0/0	0	0	0	0	0	7.54	33930.0	-	-	-
46/46	121	50	1553.7	579.3	2133.0	13.289	59800.5	2133.0	25870.5	12.1
92/46	121	150	1553.7	1737.9	3291.6	16.294	73323.0	1158.6	13522.5	11.7
92/69	181.6	125	2331.8	1448.2	3780.1	17.388	78246.0	488.5	4923.0	10.1
138/46	121	250	1553.7	2896.5	4450.2	210.0	94500.0	670.1	16254.0	24.3
194/69	181.6	346.7	2331.8	4016.8	6348.6	221	99450.0	1898.4	4950.0	2.6
194/92	242.0	321.7	3107.4	3727.2	6834.6	234	105300.0	486.0	5850.0	12.0

Conclusion and recommendation

To improve the productivity of potatoes through NP nutrient management-intensive on-farm research was conducted for three consecutive rainy seasons in northwestern Ethiopia. The finding of the research proved that the yield was improved by two and half fold for the case of south Gondar and by threefold for the case of Yimna Densa. The findings of the research have a tremendous implication on bridging the nutritional and food securities of the nation in general and the northwestern parts of the country in particular as 40% of potato growers are concentrated in this part of the country and potato are better off in nutritional contents. The result revealed that soil fertility management plays a major role in the productivity of potatoes. The research indicated that the response to nitrogen was stronger than the response to phosphorus. The tuber yield of potato was not reduced to the extent of 194 kg N ha^{-1}, it rather increased with increasing N rates, indicating we should focus on nitrogen fertilizers to maximally increase the productivity and profitability of potato production. With the current increased trends of potato demands throughout the county, the application of maximum rates of nutrients could lead to more production, profitable and sustainable potato business. For Yilmana Densa and similar niches, 138 kg N ha^{-1} and 46 kg P_2O_5 ha^{-1} are recommended as the first option followed by 138 kg N ha-1 and 69 kg P_2O_5 ha^{-1} as the second option. For south Gondar, 138 kg N ha^{-1} and 46 kg $P_2O_5ha^{-1}$ are recommended. For south Gondar, the productivity was lower than Yilmana Densa that needs further work on other management aspects. Furthermore, the recommendations could be subjected to change upon fluctuations in the farm price of potato and the cost of fertilizers.

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