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Agroecological intensification of potato (*Solanum tuberosum* L.) cultivation for sustainable and increased productivity in the Torbat-e Heydariyeh region of Iran

Fatemeh Moallem Banhangi[1], Parviz Rezvani Moghaddam[1]*, Surur Khorramdel[1], and Mehdi Nassiri Mahallati[1]

Abstract

The first step to achieving ecological sustainability and intensification in agricultural systems is to have a comprehensive agroecological analysis of agricultural systems. This research analyzed the agroecological ecosystem of potato cultivation in the Torbat-e Heydariyeh region of Iran over fifteen years (2001-2016). Based on the results, potato yield increased by 0.28 kg.ha^{-1}.yr^{-1}. The study showed that the average potential yield of potato was calculated by the FAO method to be 64 t.ha^{-1}; also, the potential yield did not increase significantly during the study period. The average yield gap of potato was calculated to be 32.44 t.ha^{-1}. Also, with increasing yield, the yield gap showed a decreasing trend. The ecosystems experienced a steady rise in intensification, and the stability has decreased. It was observed that even though nitrogen fertilizer application was increased, its efficiency dropped from 110 kg tuber per kg of nitrogen fertilizer to 70 kg. Due to the decreasing trend of NUpE (Nitrogen uptake efficiency) and NUE (Nitrogen use efficiency) during the studied years, the NUE gap was the main factor in increasing nitrogen consumption, increasing intensification, and reducing stability in the studied systems. Therefore, changing the management method to increase the efficiency of nitrogen consumption can be suggested as the first step for moving towards ecological intensification and improving the sustainability of potato growing systems.

Keywords: Fertilizer, Nitrogen use efficiency, Potential yield, Stability, Yield gap.

1. Introduction

Currently, most agricultural ecosystems face higher rates of chemical application and intensification (Lanz *et al*., 2018; Wan *et al.,* 2019b; Wan *et al.*, 2020b; Deb *et al.*, 2020).

[1] Department of Agrotechnology, Faculty of Agriculture Ferdowsi University of Mashhad, P. O. Box: 91775-1163, Mashhad, Islamic Republic of Iran.
*Corresponding author; e-mail: rezvani@um.ac.ir

Intensification has played the most crucial role in shaping the structure of agriculture over the past decades in different parts of the world. According to the European Commission, intensification consists of increasing agricultural inputs per hectare of arable land, increasing production per unit area, or increasing production in exchange for agricultural labor (Commission European, 2017). It is only possible to produce more agricultural products by increasing the intensification of conventional agricultural systems without significant environmental damage (Rasmussen *et al*., 2018).

Agricultural intensification has been recognized as one of the main reasons for biodiversity loss and related decline in ecosystem functioning due to the conversion of natural habitats into monoculture farming areas (Wan *et al.*, 2019a). Agricultural intensification has given rise to negative impacts on ecosystems, such as a reduction in the diversity of pollinating insects (Raven and Wagner., 2021), a reduction in biological control (Cusumano *et al.*, 2020), and damage to the environment from the excessive use of synthetic pesticides and mineral fertilizers (Wan *et al.*, 2020a). In addition, at the same time as climate change increases, due to the increase in the use of chemical pesticides, herbicides, and poisons, the yield stability of many agricultural systems has decreased and has led to an increase in the yield gap (Silva *et al*., 2021; Silva *et al*., 2022; Maulu *et al*., 2021). Therefore, developing sustainable alternatives to reduce chemical fertilizers, pesticides, herbicides, and other agricultural inputs is one of the main challenges. Achieving this goal is challenging without reducing production and overall yield as the demand for agricultural products steadily increases (Blösch *et al*., 2023).

Jhariya *et al.* (2021) believe that one of the major problems in organic agriculture is that implementing eco-farming technologies does not fulfill the growing demand for food worldwide. Organic farming, while reducing many negative environmental impacts, is usually associated with yield losses and therefore requires more land for the same production volume, which negatively impacts biodiversity and may not solve all these problems (Tscharntke *et al.*, 2021). In contrast, ecological intensification attempts to minimize adverse environmental impacts while simultaneously meeting growing demands for agricultural products (Blösch *et al*., 2023).

"Ecological intensification" is defined as using natural processes to replace human-produced inputs like pesticides and fertilizers while maintaining or increasing food production per unit area (Gaitán-Cremaschi *et al*., 2020; Pardo *et al.*, 2023 Wan *et al.*, 2020b). Ecological intensification through agricultural diversification, where additional crops are grown in space and time, and more robust provision of ecosystem services, such as enhanced soil fertility and natural pest and weed control, has been advocated as a sustainable approach to reducing yield gaps (Silva *et al*., 2022). The FAO defines ecological intensification as the maximum initial production per unit area without compromising the system's ability to maintain production capacity (FAO, 2009).

The concept of "ecological intensification" has been promoted to redesign agroecosystems based on the increased use of ecological processes and biodiversity, using resources more efficiently, and decreasing anthropogenic inputs (Wan *et al.,* 2019b). Ecological intensification emphasizes reducing the difference between potential and actual yield by increasing input use efficiency (Macedo *et al.*, 2021). Increasing biodiversity is one of the most important solutions for ecological intensification (Kremen, 2020). Increasing agrobiodiversity through methods such as mixed culture (Joshi *et al*., 2020), the use of cover plants (Abdalla *et al.*, 2019), and rice-fish co-culture (Wan *et al.,* 2019b). Agrobiodiversity can influence and provide numerous ecosystem services in terrestrial ecosystems (Pfiffner *et al.*, 2019).

Also, Agrobiodiversity can increase primary production and crop yields, promote natural pest and disease control, and reduce the use of chemical pesticides (Wan *et al*., 2020b). Other ways to increase ecological intensification are the use of conservation tillage (Frøslev *et al*., 2022), the use of organic and biological fertilizers (Köninger *et al.*, 2021), the use of symbiotic benefits (Zytynska and Meyer., 2019), Agroforestry (Udawatta *et al.*, 2019). The first step to achieving sustainability and ecological intensification in agricultural systems is to have a comprehensive agroecological analysis of farming systems in each region.

Over the past decade, there has been a growing body of literature concerning yield gap, stability, and sustainability in different parts of Iran (Nehbandani *et al*., 2021; Dehkordi *et al*., 2020; Alasti *et al.*, 2020; Dadrasi *et al.*, 2020). Most of these studies have been carried out over larger scales and neglected local variations in crop yield, which necessitates local scale studies (Neumann *et al*., 2010). Before creating a general plan to move towards ecological intensification, studies are needed to determine the overall picture of the ecological characteristics of the agricultural systems of each region according to the type of farming system. Such studies will provide a scientific framework for similar research to continue in other ecosystems at the local scale. Based on this data, the best program can be designed and implemented to move towards ecological intensification for each region. Potato (*Solanum tuberosum* L.) is a significant food crop cultivated in 79% of the world, with an annual production of 370.4 million tons (Gustavsen 2021; FAO, 2019). Potato ranks fourth after wheat, rice, and corn (FAO, 2019) and requires comprehensive agroecological studies. Therefore, with the formulation of the best agricultural program to move towards ecological intensification in the potato cultivation systems in the Torbat-e Heydariyeh region, northeastern Iran, this research uses a systematic method to conduct an ecological analysis of potato agricultural systems. The results of this study have determined the general picture of the ecological features of potato cultivation systems in the Torbat-e Heydariyeh region, and using this information, the best program can be designed and implemented to move towards ecological intensification.

2. Materials and Methods

2.1. Data collection

In order to study the potato cultivation systems in the Torbat-e Heydariyeh region (Figure 1), data were collected on the area under cultivation, yield, and input consumption (including water, nitrogen and phosphorus fertilizers, and chemical pesticides) from 2001 to 2016.

Torbat-e Heydariyeh is located between latitudes 35°.2798´ N and longitudes 59°.2161' E, encompassing an area of about 3900 km2, and the average altitude of the city is 1333 m above sea level (Akbari *et al*., 2018).

Data was acquired from the Ministry of Agriculture (Ministry of Agriculture-Jahad, 2016) and other related organizations and direct interviews with the farmers. In addition, data on climatic parameters (including daily minimum and maximum temperatures, precipitation, and sunny hours) were collected from the Torbat-e Heydariyeh meteorological station.

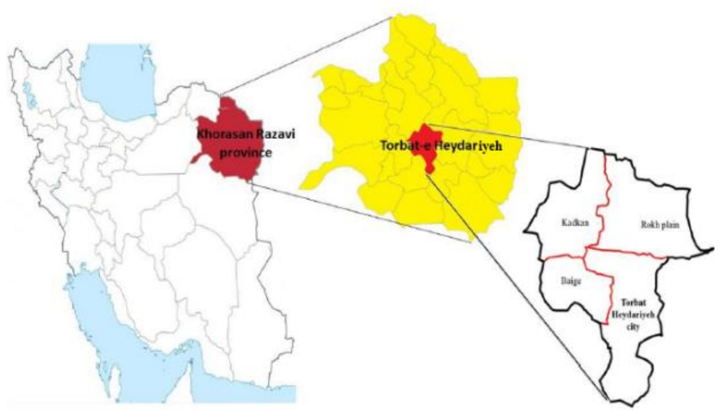

Figure 1. Study location.

2.2. Potential yield estimation by the FAO method

The method proposed by FAO for agroecological crop zoning (FAO, 1978; FAO, 1981) requires calculating the growth rate in the linear phase (LGR, $kg.ha^{-1}.day^{-1}$) and total dry matter production (TDM, $kg.ha^{-1}$) under potential environmental conditions via eq. 1 and 2:

$$LGR = \frac{0.72 \times GPHOT}{(1 + 0.25 \times C_i \times p)} \quad (1)$$

$$TDM = \frac{0.36 \times GPHOT}{(\frac{1}{p} + 0.25 \times C_i)} \quad (2)$$

GPHOT is the average rate of gross canopy photosynthesis (kg $glucose.ha^{-1}.day^{-1}$), *p* is the length of the growing period (172 assumed to be the number of days), and Ci is the maintenance respiration coefficient. The constant values are related to growth respiration and adjusted maintenance respiration coefficient. Ci is a function of temperature, and its value for legume and non-legume species can be obtained from Figure 2.

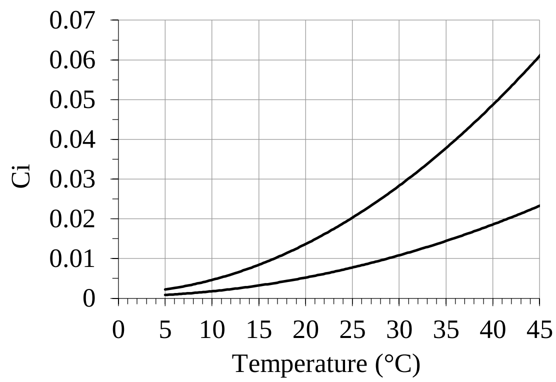

Figure 2. Relation between the coefficient of maintenance respiration (Ci in Equations 5 and 6) and average growth period temperature for 1) non-leguminous species and b) leguminous species. Source: Versteeg and van Keulen, 1986.

The GPHOT value is obtainable from Figure 3 for each level of daily solar radiation. Here, the GPHOT value is estimated based on the maximum light-saturated leaf photosynthesis rate (Fg, kg CO_2. $ha^{-1}.hr^{-1}$) and requires prior knowledge of Fg's value. In addition to plant species, leaf photosynthesis is also a function of temperature. Fg is the maximum photosynthetic capacity of a single leaf at different temperatures. Figure 4 illustrates Fg values for different groups of crops in a wide range of temperatures.

According to this figure, Fg for potato approaches 40 kg CO_2. $ha^{-1}.hr^{-1}$ at 20 °C. Referring to the values in the right section of Figure 3, the GPHOT value for potatoes under the daily radiation of 20 $MJ.m^{-2}$ is equivalent to 420 kg glucose. $ha^{-1}.hr^{-1}$.

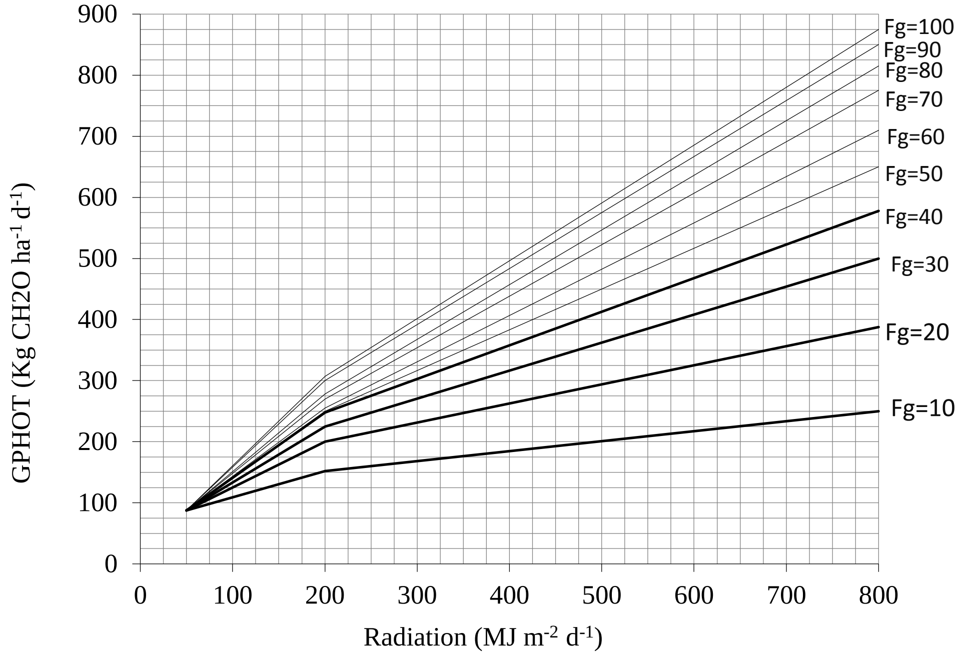

Figure 3. Daily gross photosynthesis rate (GPHOT, kg CH_2O $ha^{-1}d^{-1}$) for closed canopy (linear growth period) as a function of maximum photosynthesis rate of the single leaf at light saturation (Fg, kg CO2 $ha^{-1}h^{-1}$) and daily radiation (MJ $m^{-2}d^{-1}$) in latitudes between 0-40. Source: Versteeg and van Keulen, 1986.

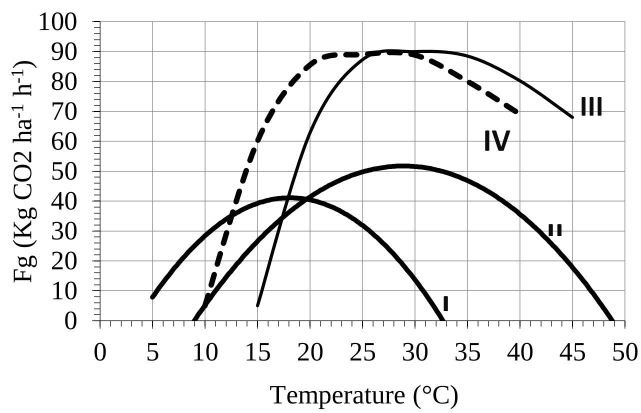

Figure 4. Relation between maximum photosynthesis rate of the single leaf at light saturation (Fg, kg CO2 ha-1h-1) and temperature in 4 groups of crop species: I) Temperate C3 species (wheat, barley, potatoes, sugar beet), II) Warm climate C3 species (rice, soybean, cotton, cassava), III) C4 species (corn, sorghum. millet, sugarcane) IV) cultivars of C4 species (corn, sorghum) adapted to the lower temperature, Fg is the same as group III but in 5 C° lower temperature. Versteeg and van Keulen, 1986**.**

Eventually, once the total dry matter production (TDM, kg.ha^{-1}) is calculated, annual crop yield could be estimated based on the harvest index (harvest index was assumed to be 80% for potato (Victorio *et al.*, 1986). Next, the results obtained from the FAO method were validated using the Root Mean Square Error (RMSE) test. RMSE is the standard deviation of the residuals (prediction errors) (Eq. 3). Here, values lower than 10% indicate an excellent simulation, while values between 10-20% indicate simulations to be satisfactory, between 20-30% moderate, and more than 30% poor (Jamieson *et al.*, 1991).

$$RMSE(\%) = \sqrt{\frac{\sum_{i=1}^{n}(P_i - O_i)^2}{n}} \times \frac{100}{\bar{O}} \qquad (3)$$

2.3. Estimating yield gap

The yield gap is the difference between the potential and actual yields, measured as:

$$YG_i = YF_i - Ya_i \qquad (4)$$

The yield gap is the difference between the estimated potential yield (YF_i) and the maximum observed actual yield (Ya_i).

2.4. Intensification

This study evaluated the intensification of potato cultivation in the Torbat-e Heydariyeh by two different methods.

2.4.1. Intensification evaluation based on inputs:

The cost index was used to calculate intensification for farm inputs, including common chemical fertilizers, urea fertilizer (46% nitrogen), and triple superphosphate (46% P2O5). Finally, intensification was evaluated based on the incurred cost index (Commission European, 2017). The average price of each input per year was obtained from www.indexmundi.com website to calculate each input cost.

2.4.2. Intensification evaluation based on outputs:

Physiologically, output intensification increases production per unit of area and time (Hunt, 2000). Therefore, potato production per year per unit area was calculated and plotted for the studied period to calculate the intensification.

2.5. Yield stability evaluation

Potato yield stability was evaluated via two different methods in this study:

2.5.1. Evaluation of yield stability based on regression residuals:

The yield regression equation for different crops over consecutive years indicates yield variation. The residuals of this regression equation point to the differences between annual actual and predicted yields and hence reflect the impact of environmental conditions (climate) on yield and can be considered an indicator of yield stability.

In order to accurately calculate the regression residuals, it is mandatory to primarily obtain a suitable regression model to describe crop yield variations. A low R-squared value indicates more significant regression residuals, which are unreliable results. In light of this fact, we used linear regression (Eq. 5), two-segment (Eq. 6), and three-segment linear regression (Eq. 7) models to explain the crop yield trend of each crop (Calderini and Slafer, 1999; Verón *et al*., 2004) and the best model was selected based on the highest coefficient of determination and normality of their residual distribution (Calderini and Slafer, 1999).

Linear	$Y = a + bx$		(5)
Two-segment linear	$Y = a + bx$	if $x \leq c$	(6)
	$Y = a + bc + d(x\text{-}c)$	if $x < c$	
Three-segment linear	$Y = a + bx$	if $x \leq c$	(7)
	$Y = a + bc + d(x\text{-}c)$	if $e \leq x < c$	
	$Y = a + bc + d(e\text{-}c) + f(x - c)$	if $x < e$	

Where Y is the yield, x is the year (2001 to 2016), a is the intercept, b is the rate of yield increase during the first linear segment, c is the year in which the first turning point occurs, d is the rate of yield increase during the second linear segment, e is the year in which the second turning point of the trend occurs, and f is the rate of yield increase during the third linear segment (Calderini and Slafer, 1999; Verón *et al*., 2004). After model selection, the regression model calculated the difference between actual and predicted performance as the yield residuals. Since only the changes in absolute yield magnitude are essential for stability assessment, the absolute magnitude of all yield residuals was calculated. Next, the yield residuals were divided by the actual yield to obtain the relative yield residuals to ascertain the ratio between yield residuals to actual yield in a given year (Calderini and Slafer, 1998). Finally, each product's trend of yield stability was obtained by plotting the relative yield residuals over time.

2.5.2. Evaluation of yield stability based on the coefficient of variation:

The coefficient of yield variation was calculated in two-year intervals by dividing the standard deviation by the average yield every two years. The linear regression equation was used to determine the trend direction of the coefficient of yield variation. The positive slope of this equation (b) indicates the increase in instability, the negative slope indicates stability improvement, and the zero slopes indicate relative stability.

2.6. Nitrogen use efficiency

Nitrogen uptake efficiency (NUpE) as the amount of nitrogen uptake by the plant per unit of nitrogen in the soil and nitrogen use efficiency (NUE), including economic yield per kg of nitrogen used, was obtained from Equations 8 and 9 (Moll *et al*., 1982):

$$NUpE = \frac{N_u}{N_f} \times 100 \qquad (8)$$

$$NUE = \frac{GY_{fertilized} - GY_{unfertilized}}{N_f} \qquad (9)$$

Nu is the amount of nitrogen uptake by the plant (kg.ha^{-1}), and Nf is the soil nitrogen content (nitrogen fertilizer applied and soil and seed nitrogen content). The annual dry matter yield was initially calculated by dividing the economic yield by the harvest index (potato dry matter content was considered 22% (Hansen *et al*., 2010) to estimate the amount of nitrogen absorbed by the plant. The difference between dry matter yield and economic yield will determine the annual biomass yield.

Finally, plant nitrogen uptake was obtained from the sum of nitrogen from the economic product (the product of nitrogen percentage and economic yield) and biomass nitrogen content (the product of biomass nitrogen content (%) and biomass yield). Nasiri Mahallati and Koocheki (2017) provided a detailed account of obtaining the components of equation 8 for wheat on the ecosystem scale.

In Equation 9, GY fertilized is the economic yield with nitrogen consumption, and GY unfertilized is the economic yield without nitrogen consumption. In practice, unfertilized yield is obtained from the control treatment. Since we did not include any control treatment in this study, the regression line intercept (Eq. 10) between economic yield (GY) and the corresponding amount of fertilizer applied (Nf) was considered as GY unfertilized.

$$GY = a + PNP \times N_f \qquad (10)$$

The intercept of this line gives the GY unfertilized in Equation 9, and the slope provides the ratio of economic yield per unit of fertilizer used, showing the average partial nitrogen productivity (kg of grain per kg of nitrogen consumed) (Cassman, 2001).

3. Results and Discussion

The results revealed an increasing potato cultivation area over the studied 15 years in the Torbat-e Heydariyeh, where a sum of 113 hectares was added to the available land (Figure 5).

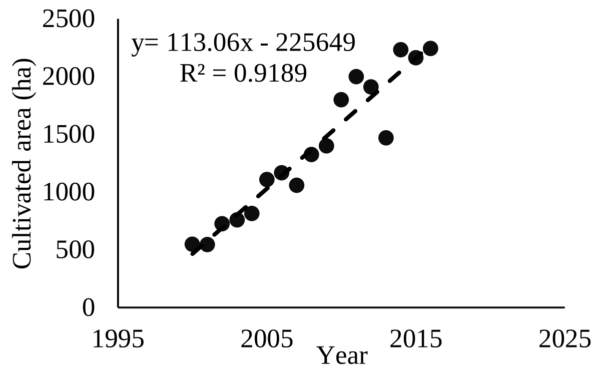

Figure 5. Variations in potato cultivation area in the Torbat-e Heydariyeh.

Increased cultivated area and cropping intensity increases agricultural production (Lu *et al.*, 2019), but the increase in agricultural production by increasing the cultivated area seems limited (Ramankutty *et al.*, 2018). The increase in the cultivated area has had little effect on the increase in food production in the world, and the increase has influenced the increase in food production in the world in yield per unit area (Timsina, 2018).

The results revealed that the Torbat-e Heydariyeh had experienced considerable fluctuations in potato yield from 2001-2016. Accordingly, the highest coefficient of determination among linear, two-segment linear, and three-segment linear regression methods was obtained for the linear regression method as merely 0.28 (Figure 6).

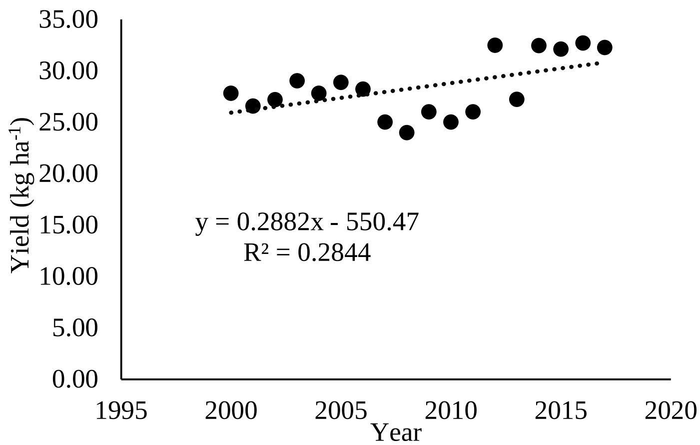

Figure 6. Potato yield variations in the Torbat-e Heydariyeh.

The studied period is characterized by 0.28 kg.ha^{-1}.yr^{-1} increase in potato yield. Parvizi and Asadian (2017) reported an increase in average yield from 27 t.ha^{-1} in 2006 to more than 30 t.ha^{-1} in 2013. Increasing the yield can be achieved with the help of plant breeding methods and improving the potential yield in the region (Morales *et al.,* 2020) or with the help of crop management and improving the actual yield and reducing the yield gap in the region (Deng *et al.*, 2019). Potential yield refers to the yield of a compatible crop in an environment with no restriction of water and nutrients and effective control of pests, diseases, and weeds. The crop growth rate in potential yield is determined solely by environmental factors and crop characteristics (Folberth *et al*., 2020).

Potential yield over the study period was estimated using the FAO method. The results obtained from the FAO method were validated by determining using RMSE. RMSE was calculated to be 15%, indicating a good model performance. The results suggested a relatively constant actual potato yield (65 t.ha^{-1}) over the studied period; the trend did not increase significantly (Figure 7).

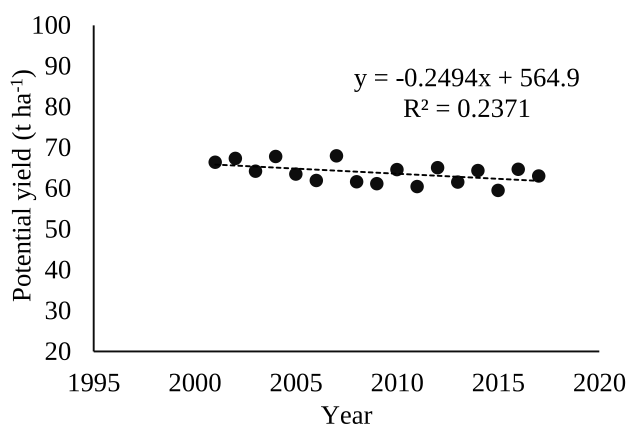

Figure 7. Potential yield of potato obtained via the FAO method**.**

The increase in potato yield during the study period in the region was not a result of the increase in the potential yield of potato. Hence, the trend of the yield gap in potato was examined. The difference between the potential yield and the maximum actual yield obtained in a region is called the yield gap (Zhao et al., 2023).

The highest practical potential yield for the area was determined from the recorded values (leading farmers), datasets of the Department of Agriculture, results of the research projects conducted under potential environmental conditions, and direct interviews with the staff of the relative organizations. The data was split into quartiles, and the average of the third quartile was considered the highest practical potential yield for the region (Personal communication). The results suggested a 20-38% yield gap for potatoes in the region (Figure 8). However, the data indicated a decreasing trend in the yield gap (Figure 8).

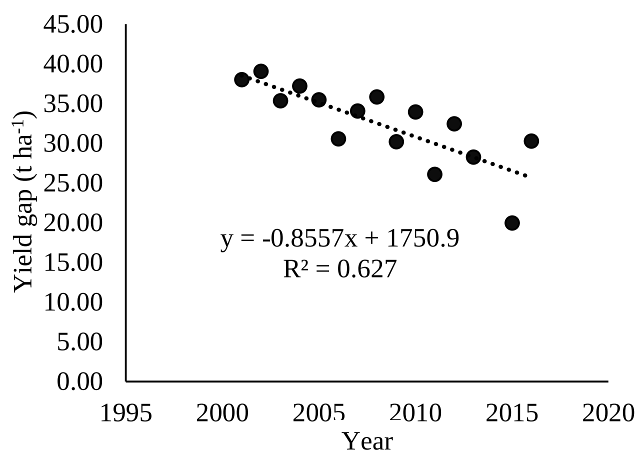

Figure 8. Potato yield gap trend in the Torbat-e Heydariyeh region.

According to the obtained results, the stability of the potential yield (Figure 7) shows that the yield gap reduction is achieved by increasing the actual yield in the region. Actual yield is affected by crop improvement and management of agricultural systems in each region. Studies show that the most critical factors in increasing the yield of agricultural products in recent years have been intensive management and the use of various technologies, intensive tillage, chemical fertilizers, pesticides, and herbicides (Kopittke *et al*., 2019; Xie e*t al.*, 2019).

In this study, intensification was evaluated based on input and output parameters. The cost index was used for the significant chemical fertilizers (urea and ammonium superphosphate) based on the input parameters in the first method. By calculating the consumption costs per hectare per year, a 15-year cost-based intensification trend was plotted. All prices were calculated in US dollars (www.indexmundi.com). According to the results, the intensification rate increased from $ 44 per hectare in 2001 to $ 120 per hectare in 2016 (Figure 9). The increase in intensification in 2007 resulted from the sudden upsurge in the global urea fertilizer price (www.indexmundi.com). Providing farmers with fertilizers, pesticides, and seeds at low prices has been one of the supportive policies of the Iranian government since 1977, pursuing the aim of self-sufficiency in the agricultural sector. Studies show that the average urea consumption in Iran is 38% higher than the global average (Rahman and Zhang, 2018), leading to the intensification of agricultural systems and, therefore, environmental consequences and lower input use efficiency.

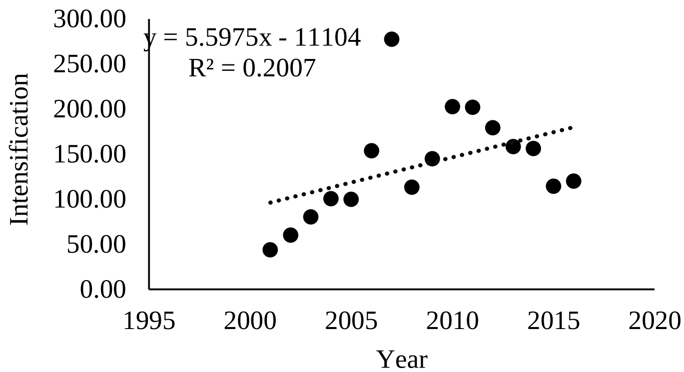

Figure 9. Changes in the intensification of potato cultivation systems in the Torbat-e Heydariyeh region.

We also used output-based indicators to calculate agriculture intensification. Physiologically, output intensification increases output per unit area and time (Alekseychik *et al.*, 2019). The Evaluation of intensification based on the amount of potato production per area in the Torbat-e-Heydariyeh region shows an increasing trend in potato production between 2001 and 2016 (i.e., production per unit area grew by 9% over time), which indicates an increase in intensification of potato growing systems in the study area (Figure10).

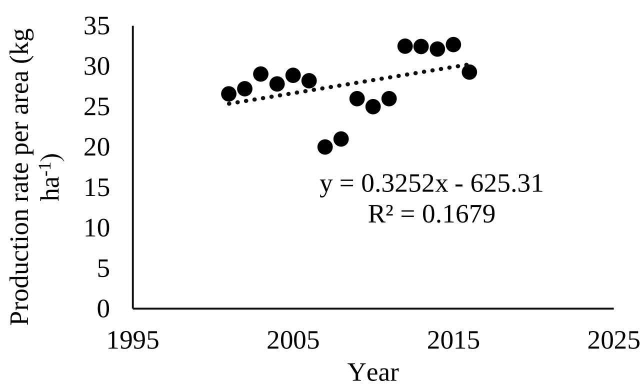

Figure 10. Changes in potato production per unit area in the Torbat-e Heydariyeh region.

Studies show that expanding intensification through management methods affects yield stability (Xie *et al.*, 2019). Stability is an essential component of crop ecosystem sustainability and expresses the intensity of yield fluctuations in the face of short-term environmental changes and is a criterion of year-to-year yield fluctuations in an area (Stomph *et al*., 2020). The researchers have proven that narrowing the yield gap and increasing yield will ensure food security if accompanied by yield stability (Skaf *et al.*, 2019). Therefore, we attempted to ascertain whether the observed improvement in potato yield in the region is sufficiently stable. Interestingly, despite improved crop yield, crop yield stability deteriorated simultaneously. The regression equation's residual values indicated annual yield fluctuations of 2.94 to 14.75 % around the predicted values. These yield residual fluctuations suggest a shift towards instability at an annual rate of 28% (Figure 11). Our results also indicated an increasing trend in the absolute values of regression residuals over the past 15 years (Figure 9), leading to yield fluctuations in the range of 0.78 to 3.94 t.ha^{-1} (Figure 11). Khan *et al.* (2021) indicated crop yield improvements over the past decade thanks to the introduction of modern farming practices, closing the yield gap. However, this closing yield gap has been concurrent with the instability in farming systems. Several studies have mentioned the inverse relationship between yield and stability in agricultural systems (Calderini and Slafer, 1998; Urruty *et al*., 2016; Stomph *et al*., 2020).

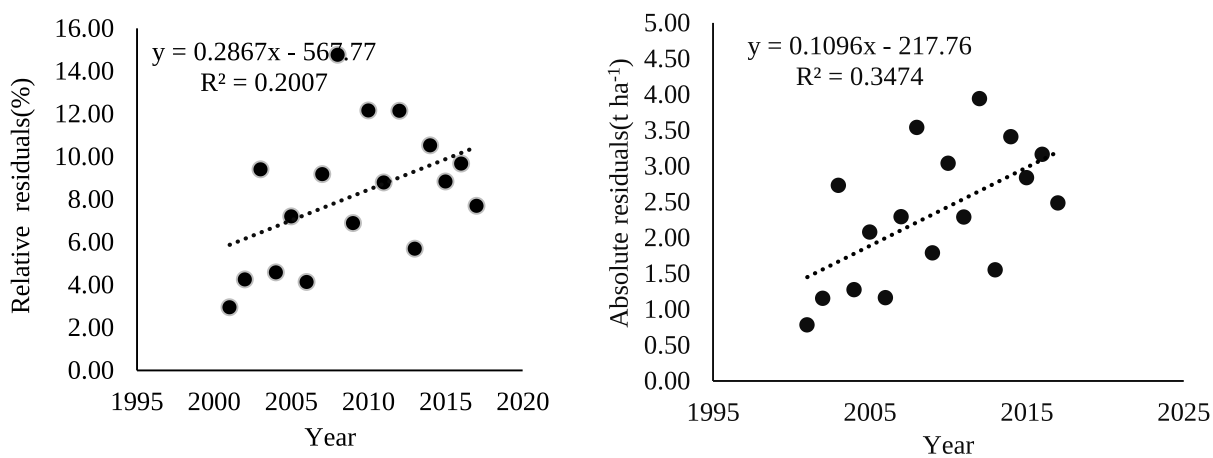

Figure 11. Changes in absolute and relative residual values of potato yield in the Torbat-e Heydariyeh region.

Calculating the coefficient of variation is another method for yield stability analysis. As a simple and widely used index, the coefficient of variation measures the standard deviation of yield values relative to the mean in different environments and periods. Therefore, higher values of the coefficient of variation in yield will indicate more significant fluctuations and greater yield instability (Ray *et al*., 2015). For example, the coefficient of variation had a relatively constant value over the period (-0.0006) while shifting between 0.007 and 0.124, indicating high degrees of instability in potato cultivation systems in the region over 2001-2016 (Figure 12).

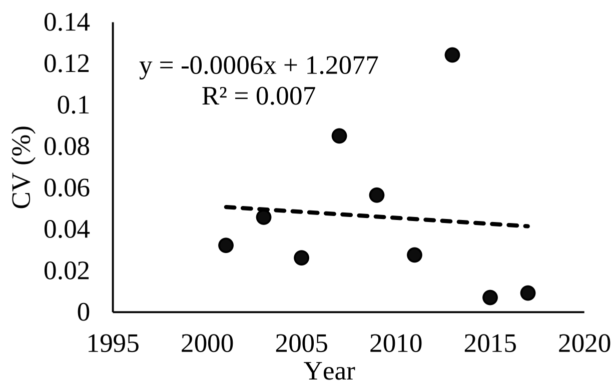

Figure 12. Changes in the coefficient of variation of potato yield in the Torbat-e Heydariyeh region.

The findings also suggested a growing trend in the absolute value of the crop yield residuals over the years while adding to the area under potato cultivation. These results suggest that increasing the cultivation area could lower crop yield stability in the region (Figure 13).

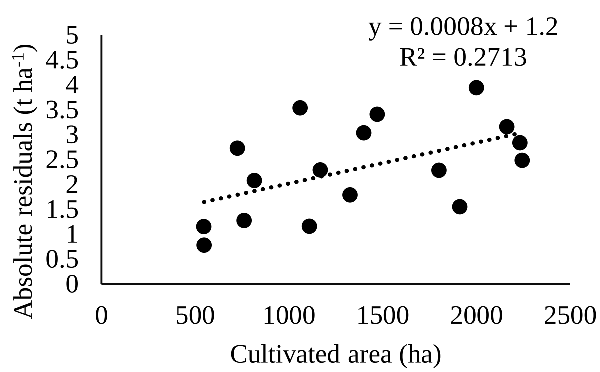

Figure 13. The absolute value of the potato yield residuals as a function of cultivation area.

A decrease in yield stability indicates that the increase in potato yield in the study area will not be sustainable in the long term. Considering that the Torbat-e Heydariyeh is one of Iran's leading centers of potato production, failure to change these ecosystems' management style in the long term will lead to a sharp decline in production and yield .One of the most important factors affecting crop yield stability is fertilizer use efficiency (Stomph *et al*., 2020). The industrial production of chemical fertilizers, especially nitrogen fertilizers, was one of the most significant technological advances in agriculture in the 20th century (Guo et al., 2021). Nitrogen fertilizers' contribution to improving yield has been reported to be between 30 to 50% (Ahmed *et al*., 2017).

According to the reports, global nitrogen fertilizer consumption increased from 13.5 million tons in 1962 to 189.5 million tons in 2019 (FAO, 2019). On the other hand, 50% of the energy used in agricultural production is related to the industrial production of nitrogen fertilizers (Kaab *et al*., 2019). The increase in chemical fertilizer use decreased efficiency and stability (Haroon *et al*., 2019; Chen et al., 2018b).

Improving nitrogen use efficiency is a crucial strategy to promote sustainable agricultural systems, which leads to maximum yield in exchange for minimum inputs and nitrogen wastage (Dimkpa *et al*., 2020).

In this regard, the trend of changes in nitrogen uptake and use efficiency in the studied years in the ecosystem of the Torbat-e Heydariyeh potato growing systems were studied.

We found that increasing nitrogen fertilizer application could lower nitrogen uptake efficiency from 48% to as low as 34% (Figure 14).

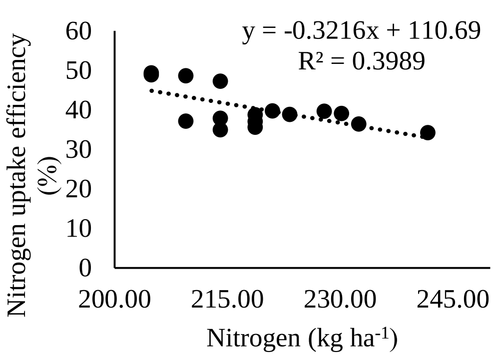

Figure 14. Nitrogen uptake efficiency of potatoes in the Torbat-e Heydariyeh region.

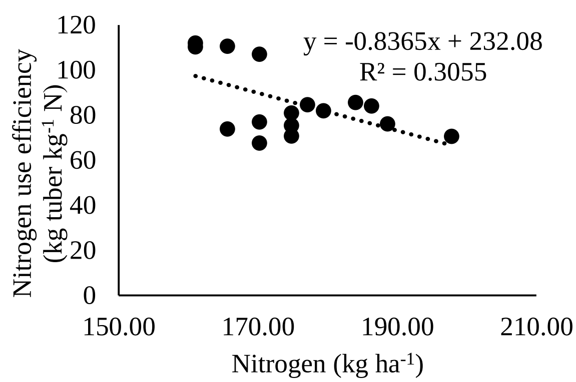

Figure 15. Nitrogen use efficiency of potatoes in the Torbat-e Heydariyeh region.

During the study, increasing nitrogen fertilizer application lowered nitrogen use efficiency from 110 kg of tubers per kg of nitrogen to 70 kg (Figure 15). Sharma and Bali (2018) examined the methods of improving nitrogen use efficiency and stated that increasing nitrogen fertilizers' application could lower nitrogen use efficiency.

The nitrogen use efficiency gap has been the main factor in increasing nitrogen consumption, increasing intensification, and reducing stability in potato growing systems in the Torbat-e Heydariyeh. Therefore, programs related to changing the management methods of ecological intensification with intensification in this region should initially focus on increasing nitrogen use efficiency.

Generally, the possible actions to increase nitrogen use efficiency to increase ecological intensification can be divided into biotechnological breeding and agricultural-management measures. One possible measure to increase nitrogen use efficiency is to genetically modify plants to improve the efficiency of resource consumption, particularly nitrogen consumption. (Aseel *et al.*, 2019; Vidal *et al*., 2020; Zhang *et al*., 2020). Using crops that absorb nitrogen more efficiently is a more straightforward way to increase nitrogen use efficiency (Swarbreck *et al.*, 2019). Utilizing these crops will reduce the consumption of food elements by using a higher efficiency of consumption and increasing ecological intensification. In a further method of moving towards ecological intensification, plants are genetically manipulated to reduce their immune systems and increase microbial colonization in their roots. This work aims to create and increase symbiosis between nitrogen-fixing microorganisms and non-legume plants, which allows non-legume plants to benefit from symbiosis (Ryu *et al.*, 2020; Muchero *et al.*, 2018). Among the possible measures in the second group (management and agricultural measures), some biological solutions may be used for maximizing resource efficiency, reducing intensification, and increasing ecological intensification (Bargaz *et al.*, 2018). Some of these strategies include adding a nitrogen-fixing cover crop in rotation, manipulating soil microbial populations in a controlled manner, and using nitrogen-fixing bacteria in agricultural ecosystems (Schmidt *et al.*, 2018; Igiehon and Babalola, 2018). Crop rotation is one of the other effective management methods to increase nitrogen use efficiency and ecological intensification. Using legumes or other cover plants can increase nitrogen use efficiency by reducing the need to use chemical fertilizers and preventing nitrate runoff (Chen *et al.*, 2018). In addition, the absorption of washed water and the reuse of water from agricultural drainage systems can help to recover nutrients lost in runoff (Ashu and Lee, 2019). Using conservation tillage methods with their effect on the microbial population, the amount of biomass in the soil, and resource use efficiency can help increase ecological intensification in agricultural ecosystems (Alijani *et al*., 2019). Based on different results, nitrogen use efficiency increased in the conservation tillage and no-tillage systems (Yang *et al*., 2020; Jug *et al*., 2019). Studies have shown that maintaining plant residues by adjusting soil temperature and increasing biodiversity affects nitrogen absorption efficiency. The reason for this is the plant's greater access to nitrogen due to the gradual release of plant residues and chemical fertilizers (Wang *et al.,* 2018).

Conclusions

Agroecological analysis of potato cultivation ecosystems from 2001 to 2016 in the Torbat-e Heydariyeh region showed that potato yield in the study area is increasing, but this increase in yield is not stable. So sustainability of the cultivation of this product in the region endangers. According to the results of this research, the decrease in the nitrogen use efficiency was the main reason for the increase in nitrogen use, the intensification, and the reduction in stability in potato cultivation ecosystems in the Torbat-e Heydariyeh region. Therefore, planning and changing the management method to increase the efficiency of nitrogen consumption can be suggested as the first step for increasing yield, moving towards ecological intensification, and increasing the sustainability of potato growing systems in the Torbat-e Heydariyeh region.

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فشردهسازی اگرواکولوژیکی کشت سیب زمینی (.Solanum tuberosum L) با رویکرد پایداری و افزایش بهره وری در منطقه تربت حیدریه در ایران

چکیده

اولین گام برای دستیابی به پایداری و فشرده¬سازی اکولوژیک در سیستم های کشاورزی، داشتن یک تحلیل جامع زراعی از سیستم های کشاورزی است. این تحقیق به بررسی اکوسیستم های زراعی کشت سیب زمینی در منطقه تربت حیدریه ایران طی پانزده سال (1395-1380) پرداخته است. بر اساس نتایج حاصل از پژوهش، عملکرد سیب زمینی سالانه 0/28 کیلوگرم در هکتار در سال افزایش یافت. این مطالعه نشان داد که میانگین عملکرد پتانسیل سیب زمینی به روش فائو 64 تن در هکتار محاسبه شد. همچنین، عملکرد پتانسیل در طول دوره مورد مطالعه افزایش معنی داری نداشت. میانگین خلاء عملکرد سیب زمینی 32/44 تن در هکتار محاسبه شد. همچنین با افزایش عملکرد، خلاء عملکرد روند کاهشی نشان داد. در طی دوره¬ی مطالعه، در سیستم¬های مورد بررسی فشرده¬سازی افزایش و ثبات سیستم¬ها کاهش یافت. نتایج نشان داد که با وجود افزایش مصرف کود نیتروژن، کارایی آن از 110 کیلوگرم غده به ازای هر کیلوگرم کود نیتروژن به 70 کیلوگرم کاهش یافت. با توجه به روند کاهشی NUpE (کارایی جذب نیتروژن) و NUE (کارایی مصرف نیتروژن) در طول سال‌های مورد مطالعه، خلاء NUE عامل اصلی افزایش مصرف نیتروژن، افزایش فشرده-سازی و کاهش پایداری در سیستم‌های مورد مطالعه بود. بنابراین تغییر روش مدیریت برای افزایش راندمان مصرف نیتروژن را می توان به عنوان اولین قدم برای حرکت به سمت فشرده¬سازی اکولوژیکی و بهبود پایداری سیستم های کشت سیب زمینی پیشنهاد کرد.

واژه‌های کلیدی: پایداری، خلاء عملکرد، عملکرد پتانسیل، کود، کارایی مصرف نیتروژن.