

Agroecological Intensification of Potato (*Solanum tuberosum* L.) Cultivation for Sustainable and Increased Productivity in Torbat-e Heydariyeh Region, Iran

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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 t ha⁻¹ yr⁻¹. 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 decreased. It was observed that although 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 production systems.

Keywords: Nitrogen fertilizer, Nitrogen use efficiency, Potential yield, Yield gap.

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). 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

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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 affects biodiversity and may not solve all these problems (Tscharrntke *et al.*, 2021). In contrast, ecological intensification attempts to minimize adverse environmental impacts while simultaneously meeting the 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 control of natural pest and weed, 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 can be achieved 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 (Frøsløv *et al.*, 2022), the use of organic and biological fertilizers (Königer *et al.*, 2021), the use of symbiotic benefits (Zytynska and Meyer, 2019), and 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. We aimed to determine the general picture of the ecological features of potato cultivation systems in the Torbat-e Heydariyeh Region, since using this information, the best program can be designed and implemented to move towards ecological intensification.

MATERIALS AND METHODS

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 at 35° 27'98" N and longitudes 59° 21'61" E, encompassing an area of about 3,900 km², and the average altitude of the city is 1,333 m above sea level (Akbari *et al.*, 2018).

Data was acquired from the 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.

Potential Yield Estimation by the FAO Method

The method proposed by FAO for agroecological crop zoning (FAO, 1978;

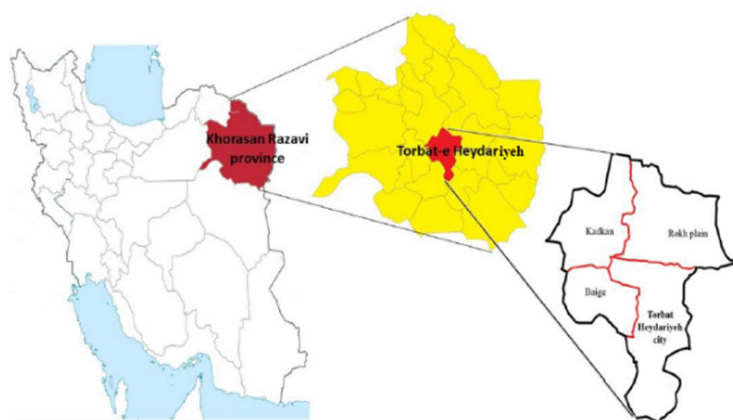


Figure 1. Location of the study area.



FAO, 1981) requires calculating the growth rate in the linear phase (LGR, kg ha⁻¹ d⁻¹) and Total Dry Matter production (TDM, kg ha⁻¹) under potential environmental conditions via Equations (1) and (2):

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

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

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

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 (F_g , kg CO₂ ha⁻¹ h⁻¹) and requires prior knowledge of F_g 's value. In addition to plant species, leaf photosynthesis is also a function of temperature. F_g is the maximum photosynthetic capacity of a single leaf at different temperatures. Figure 4 illustrates F_g values for different groups of crops in a wide range of temperatures.

According to Figure 4, F_g for potato approaches 40 kg CO₂ ha⁻¹ h⁻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 d⁻¹.

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.

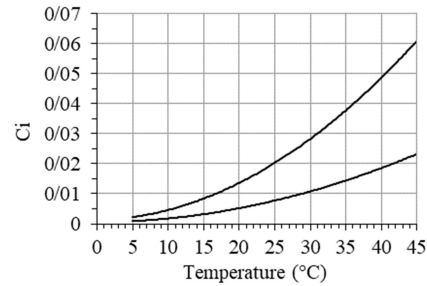


Figure 2. Relation between the coefficient of maintenance respiration (C_i in Equations 5 and 6) and average growth period temperature for (1) Non-leguminous species and (b) Leguminous species. Source: Versteeg and van Keulen, 1986.

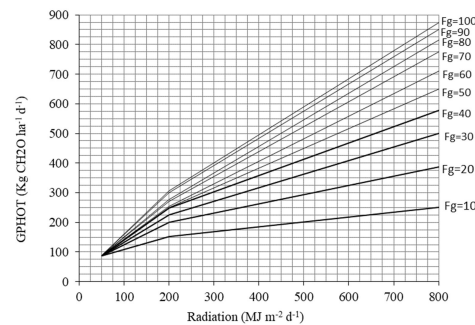


Figure 3. Daily gross photosynthesis rate (GPHOT, kg CH₂O ha⁻¹ d⁻¹) for closed canopy (linear growth period) as a function of maximum photosynthesis rate of the single leaf at light saturation (F_g , kg CO₂ ha⁻¹ h⁻¹) and daily radiation (MJ m⁻² d⁻¹) in latitudes between 0-40. Source: Versteeg and van Keulen, 1986.

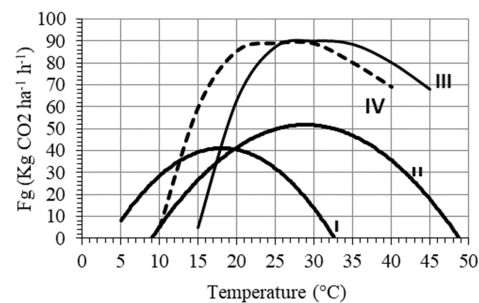


Figure 4. Relation between maximum photosynthesis rate of the single leaf at light saturation (F_g , kg CO₂ ha⁻¹ h⁻¹) and temperature in 4 groups of crop species: (I) Temperate C₃ species (wheat, barley, potatoes, sugar beet), (II) Warm climate C₃ species (rice, soybean, cotton, cassava), (III) C₄ species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

RMSE is the standard deviation of the residuals (prediction errors) (Equation 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).

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

Estimating Yield Gap

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

$$YG_i = YF_i - Y_{a_i} \quad (4)$$

The Yield Gap (YG_i) is the difference between the estimated potential Yield (YF_i) and the maximum observed actual Yield (Y_{a_i}).

Intensification

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

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% P_2O_5). 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.

Intensification Evaluation Based on Outputs:

Physiologically, output intensification increases production per unit 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.

Yield Stability Evaluation

Potato yield stability was evaluated via two different methods as follows:

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 the light of this fact, we used linear regression (Equation 5), two-segment (Equation 6), and three-segment linear regression (Equation 7) models to explain the crop yield trend of each crop (Calderini and Slafer, 1999; Verón *et al.*, 2004). The best model was selected based on the highest coefficient of determination and normality of their residual distribution (Calderini and Slafer, 1999).

$$\text{Linear} \quad Y = a + bx \quad (5)$$

$$\begin{array}{ll} \text{Two-segment} & Y = a + bx \quad \text{if } x \leq c \\ \text{linear} & Y = a + bc + d(x - c) \quad \text{if } x > c \end{array} \quad (6)$$

$$\begin{array}{ll} \text{Three-segment} & Y = a + bx \quad \text{if } x \leq c \\ \text{linear} & Y = a + bc + d(x - c) \quad \text{if } c < x \leq e \\ & Y = a + bc + d(e - c) \quad \text{if } x > e \end{array} \quad (7)$$



$$+f(x-c) \quad \text{if} \\ x < e$$

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 the 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.

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.

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):

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

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

Where, N_u is the amount of Nitrogen uptake by the plant (kg ha^{-1}), and N_f 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). Nassiri 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 use, 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 (Equation 10) between economic yield (GY) and the corresponding amount of fertilizer applied (N_f) was considered as $GY_{unfertilized}$.

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

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 ($\text{kg of grain per kg of nitrogen consumed}$) (Cassman, 2001).

RESULTS AND DISCUSSION

The results revealed an increasing potato cultivation area over the studied 15 years in the Torbat-e Heydariyeh (Figure 5).

Increased cultivated area and intensification, 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).

The studied period is characterized by 0.28 t 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 RMSE, which 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).

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

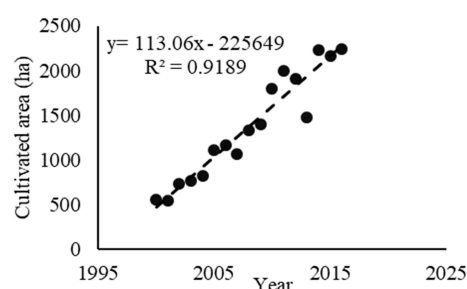


Figure 5. Variations in potato cultivation area in the Torbat-e Heydariyeh.

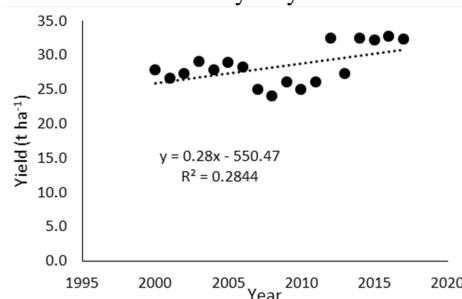


Figure 6. Potato yield variations in the Torbat-e Heydariyeh.

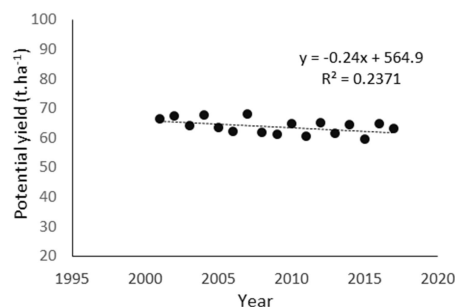


Figure 7. Potential yield of potato obtained via the FAO method.



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 related organizations. The data was split into quartiles, and the average of the third quartile was considered the highest actual potential yield for the region (Personal communication with Dr. Nassiri Mahallati). 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).

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 *et 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.

We also used output-based indicators to calculate agriculture intensification. Physiologically, output intensification increases output per unit area and time (Alekseychik *et al.*, 2019).

Evaluation of intensification based on the

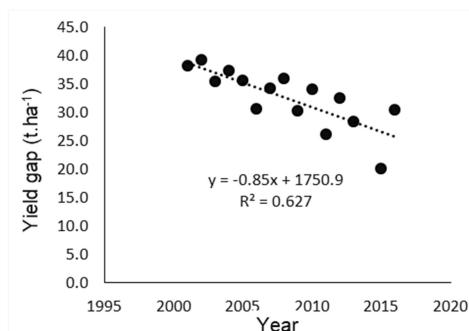


Figure 8. Potato yield gap trend in the Torbat-e Heydariyeh Region.

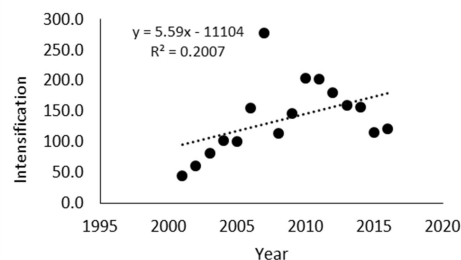


Figure 9. Changes in the intensification of potato cultivation systems in the Torbat-e Heydariyeh Region.

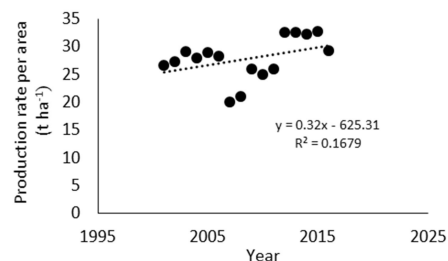


Figure 10. Changes in potato production per unit area in the Torbat-e Heydariyeh Region.

amount of potato production per unit 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 (Figure 10).

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, which 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 (Figure 10). Interestingly, despite improved crop yield, crop yield stability decreased 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 that the amount of instability increases by 28% annually." (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 of the 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).

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).

The findings also suggested a growing trend in the absolute value of the crop yield residuals over the years while adding to the

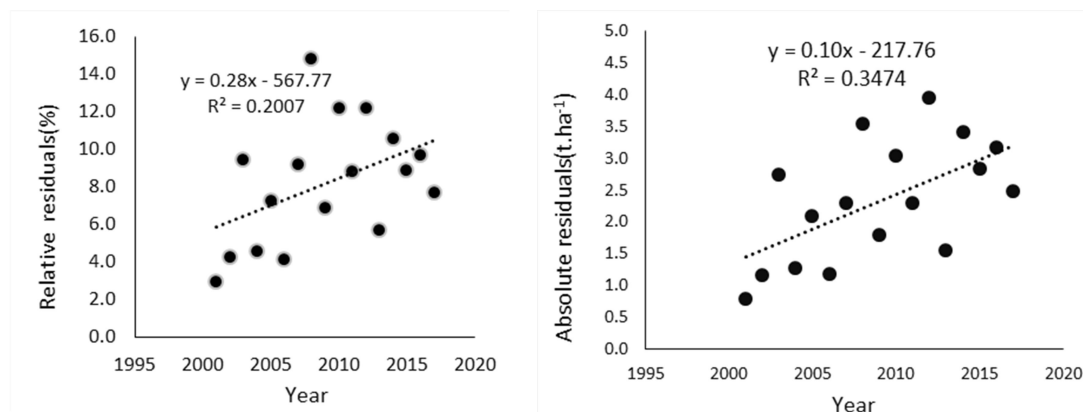


Figure 11. Changes in absolute and relative residual values of potato yield in the Torbat-e Heydariyeh Region.



area under potato cultivation. These results suggest that increasing the cultivation area could lower crop yield stability in the region (Figure 13).

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 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 (FAO, 2019), global nitrogen fertilizer consumption increased from 13.5 million tons in 1962 to 189.5 million tons in 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 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).

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 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.*,

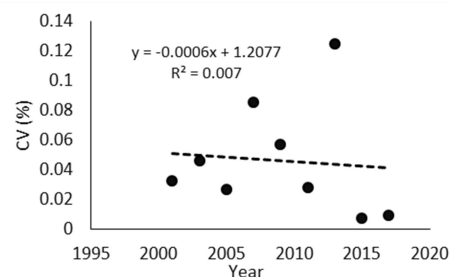


Figure 12. Changes in the coefficient of variation of potato yield in the Torbat-e Heydariyeh Region.

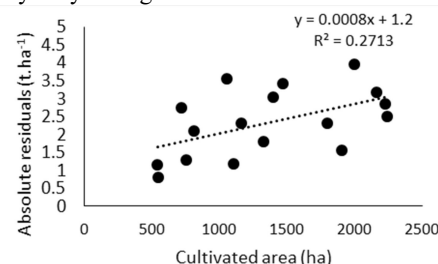


Figure 13. The absolute value of the potato yield residuals as a function of cultivation area.

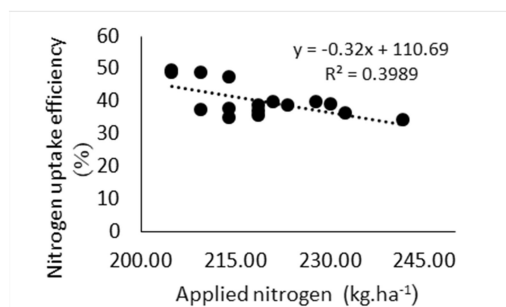


Figure 14. Nitrogen uptake efficiency of potatoes in Torbat-e Heydariyeh Region.

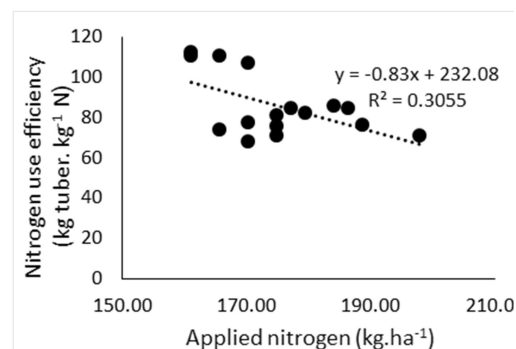


Figure 15. Nitrogen use efficiency of potatoes in Torbat-e Heydariyeh Region.

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 suppress 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 Torbat-e Heydariyeh Region, Iran, showed that potato yield in the study area is increasing, but this increase in yield is not stable, so, sustainability of potato production in the region is endangered. According to



the results of this research, the decrease in the nitrogen use efficiency was the main reason for the increase in nitrogen fertilizer use, the intensification, and the reduction in stability in potato ecosystems in 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 Torbat-e Heydariyeh Region.

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REFERENCES

1. Abdalla, M., Hastings, A., Cheng, K., Yue, Q., Chadwick, D., Espenberg, M., Truu, J., Rees, R.M. and Smith, P. 2019. A Critical Review of the Impacts of Cover Crops on Nitrogen Leaching, Net Greenhouse Gas Balance, and Crop Productivity. *Glob. Chang Biol.* **25(8)**: 2530-2543.
2. Ahmed, M., Rauf, M., Mukhtar, Z. and Saeed, N. A. 2017. Excessive Use of Nitrogenous Fertilizers: An Unawareness Causing Serious Threats to the Environment and Human Health. *ESPR*, **24**: 26983-26987.
3. Akbari, H., Soleimani, H., Radfard, M., Abasnia, A., Hashemzadeh, B., Akbari, H. and Adibzadeh, A. 2018. Data on Investigating the Nitrate Concentration Levels and Quality of Bottled Water in Torbat-E Heydariyeh, Khorasan Razavi Province, Iran. *Data Brief*, **20**: 463-467.
4. Alasti, O., Zeinali, E., Soltani, A. and Torabi, B. 2020. Estimation of Yield Gap and the Potential of Rainfed Barley Production Increase in Iran. *J. Crop Prod.*, **13(3)**: 41-60.
5. Alijani, K., Bahrani, M. J. and Kazemeini, S. A. 2019. Is It Necessary to Adjust Nitrogen Recommendations for Tillage and Wheat Residue Management in Irrigated Sweet Corn? *Arch. Agron. Soil Sci.*, **65(14)**: 1984-1997.
6. Alekseychik, T. V., Bogachev, T. V., Karasev, D. N., Sakharova, L. V. and Stryukov, M. B. 2019. Fuzzy Method of Assessing the Intensity of Agricultural Production on a Set of Criteria of the Level of Intensification and the Level of Economic Efficiency of Intensification. In *13th International Conference on Theory and Application of Fuzzy Systems and Soft Computing—ICAFS-2018*, Springer International Publishing, **13**: 635-642.
7. Alexandridis, N., Feit, B., Kihara, J., Luttermoser, T., May, W., Midega, C., Öborn, I., Poveda, K., Sileshi, G.W., Zewdie, B. and Clough, Y. 2023. Climate Change and Ecological Intensification of Agriculture in Sub-Saharan Africa—A Systems Approach to Predict Maize Yield under Push-Pull Technology. *Agric. Ecosyst Environ.*, **352**: 108511.
8. Aseel, D. G., Mostafa, Y., Riad, S. A. and Hafez, E. E. 2019. Improvement of Nitrogen Use Efficiency in Maize Using Molecular and Physiological Approaches. *Symbiosis*, **78(3)**: 263–274.
9. Ashu, A. and Lee, S. 2019. Reuse of Agriculture Drainage Water in a Mixed Land-Use Watershed. *J. Agron.*, **9(1)**: 1-18.
10. Bargaz, A., Lyamlouli, K., Chtouki, M., Zeroual, Y. and Dhiba, D. 2018. Soil Microbial Resources For Improving Fertilizers Efficiency in an Integrated Plant Nutrient Management System. *Front. Microbiol.*, **9**: 1606.
11. Blösch, S., Albrecht, M., Jenny, M., Streit, B. and Knop, E. 2023. Rows Make the Field: Winter Wheat Fields with Manipulated Crop Architecture Show Potential for Ecological Intensification Based on Higher Natural Pest and Weed Seed Control. *Agric. Ecosyst. Environ.*, **348**: 108404.
12. Calderini, D. F. and Slafer, G. A. 1999. Has Yield Stability Changed With The Genetic

- Improvement of Wheat Yield? *Euphytica*, **107(1)**: 51-59.
13. Calderini, D. F. and Slafer, G. A. 1998. Changes in Yield and Yield Stability in Wheat during the 20th Century. *Field Crop Res.*, **57(3)**: 335-347.
 14. Cassman, K. G. 2001. Crop Science Research to Assure Food Security, In: “*Crop Science: Progress and Prospects*”, (Eds.): Nosberger, J., Geiger, H. H. and Struik, P. C. CAB International Wallingford, PP. 33-51.
 15. Chen, S., Liu, S., Zheng, X., Yin, M., Chu, G., Xu, C., Yan, J., Chen, L., Wang, D. and Zhang, X. 2018a. Effect of Various Crop Rotations on Rice Yield and Nitrogen Use Efficiency in Paddy-Upland Systems in Southeastern China. *Crop J.*, **6(6)**: 576-588.
 16. Chen, H., Deng, A., Zhang, W., Li, W., Qiao, Y., Yang, T., Zheng, C., Cao, C. and Chen, F. 2018b. Long-Term Inorganic plus Organic Fertilization Increases Yield and Yield Stability of Winter Wheat. *Crop J.*, **6(6)**: 589-599.
 17. Commission European. 2017. Agri-Environmental Indicator- Intensification-Extensification. EU Rural Review, Belgium.
https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agri_environmental_indicator_-_intensification_-_extensification&oldid=350689
 18. Cusumano, A., Harvey, J. A., Bourne, M. E., Poelman, E. H. and de Boer, J. G. 2020. Exploiting Chemical Ecology to Manage Hyper Parasitoids in Biological Control of Arthropod Pests. *Pest Manag. Sci.*, **76(2)**: 432-443.
 19. Deb, D. 2020. Is the System of Rice Intensification (SRI) Consonant with Agroecology? *Agroecol. Sustain. Food Syst.*, **44 (10)**: 1338-1369.
 20. Dadrasi, A., Torabi, B., Rahimi, A., Soltani, A. and Zeinali, E. 2020. Determination of Potato (*Solanum tuberosum* L.) Yield Gap in Golestan Province. *J. Agroecol.*, **12(4)**: 613-633.
 21. Dehkordi, P. A., Nehbandani, A., Hassanpour-Bourkheili, S., Kamkar, B. 2020 Yield Gap Analysis Using Remote Sensing and Modeling Approaches: Wheat in the Northwest of Iran. *Int. J. Plant Prod.*, **14(3)**: 443-452.
 22. Deng, N., Grassini, P., Yang, H., Huang, J., Cassman, K. G. and Peng, S. 2019. Closing Yield Gaps for Rice Self-Sufficiency in China. *Nat. Commun.*, **10(1)**: 1725.
 23. Dimkpa, C. O., Fugice, J., Singh, U. and Lewis, T. D. 2020. Development of Fertilizers for Enhanced Nitrogen Use Efficiency—Trends and Perspectives. *Sci. Total Environ.*, **731**: 139113.
 24. FAO. 1978. Report on The Agroecological Zones Project. Methodology and Results for Africa. World Soil Resources Report 48/1, FAO, Rome, **1**: 158.
 25. FAO. 1981. Report on The Agroecological Zones Project. Methodology and Results for South and Central America. World Soil Resources Report 48/3, FAO, Rome, **3**: 251.
 26. FAO. 2009. *Organic Agriculture: Glossary on Organic Agriculture*. Food and Agriculture Organization of the United Nations Rome, 163 PP.
<http://www.fao.org/3/k4987t/k4987t00.htm>
 27. FAO. 2019. *The FAOSTAT Database*. Available at <http://faostat.fao.org/default.aspx>.
 28. Folberth C., Khabarov N., Balkovič J., Skalský R., Visconti P., Ciais P., Janssens I. A., Peñuelas J. and Obersteiner M. 2020 The Global Cropland-Sparing Potential of High-Yield Farming. *Nat. Sustain.*, **3(4)**: 281-289.
 29. Frøslev, T. G., Nielsen, I. B., Santos, S. S., Barnes, C. J., Bruun, H. H. and Ejrnæs, R. 2022. The Biodiversity Effect of Reduced Tillage on Soil Microbiota. *Ambio*, **51(4)**: 1022-1033.
 30. Gaitán-Cremaschi D., Klerkx L., Duncan J., Trienekens J. H., Huenchuleo C., Dogliotti S., Contesse M. E., Benitez-Altuna F. J. and Rossing W. A. 2020 Sustainability Transition Pathways Through Ecological Intensification: An Assessment of Vegetable Food Systems In Chile. *Int. J. Agric. Sustain.*, **18(2)**: 131-150.
 31. Guo, L., Li, H., Cao, X., Cao, A. and Huang, M. 2021. Effect of Agricultural Subsidies on the Use of Chemical



- Fertilizers. *J. Environ. Manage.*, **299**: 113621.
32. <https://doi.org/10.1016/j.jenvman.2021.113621>
33. Gustavsen G. W. 2021 Sustainability and Potato Consumption. *Potato Res.*, **64**: 571–586.
34. Hansen C. L., Thybo A. K., Bertram H. C., Viereck N., Van Den Berg F. and Engelsens, S. B. 2010. Determination of Dry Matter Content in Potato Tubers by Low-Field Nuclear Magnetic Resonance (LF-NMR). *J. Agric. Food Chem.*, **58**(19): 10300-10304.
35. Haroon, M., Idrees, F., Naushahi, H. A., Afzal, R., Usman, M., Qadir, T. and Rauf, H., 2019. Nitrogen Use Efficiency: Farming Practices and Sustainability. *J. Exp. Agric. Int.*, **36**(3): 1-11.
36. Hunt, R. C. 2000. Labor Productivity and Agricultural Development: Boserup Revisited. *Hum. Ecol.*, **28**(2): 251-277.
37. Igiehon, N. O. and Babalola, O. O. 2018. Rhizosphere Microbiome Modulators: Contributions of Nitrogen-Fixing Bacteria towards Sustainable Agriculture. *IJERPH*, **15**(4): 574.
38. Jamieson, P. D., Porter, J. R. and Wilson, D. R. 1991. A Test of the Computer Simulation Model ARCWHEAT1 on Wheat Crops Grown in New Zealand. *Field Crop Res.*, **27**(4): 337-350.
39. Jhariya, M. K., Meena, R. S. and Banerjee, A. 2021. Ecological Intensification of Natural Resources towards Sustainable Productive System. In: “*Ecological Intensification of Natural Resources for Sustainable Agriculture*”. Springer Nature Singapore Pte Ltd. 2021, PP. 1-28.
40. Jug, D., Đurđević, B., Birkás, M., Brozović, B., Lipiec, J., Vukadinović, V. and Jug, I., 2019. Effect of Conservation Tillage on Crop Productivity and Nitrogen Use Efficiency. *Soil Till. Res.*, **194**: 104327.
41. Joshi, B. K., Vista, S. P., Gurung, S. B., Ghimire, K. H., Gurung, R., Pant, S., Gautam, S. and Paneru, P. B. 2020. Cultivar Mixture for Minimizing Risk in Farming and Conserving Agrobiodiversity. Traditional Crop Biodiversity for Mountain Food and Nutrition Security in Nepal. Tools and Research Results of the UNEP GEF Local Crop Project, Nepal, PP. 14-24.
42. Kaab, A., Sharifi, M., Mobli, H., Nabavi-Pelesaraei, A., and Chau, K. W. 2019. Combined Life Cycle Assessment and Artificial Intelligence for Prediction of Output Energy and Environmental Impacts of Sugarcane Production. *Sci. Total Environ.*, **664**: 1005-1019.
43. Khan, I., Lei, H., Khan, A., Muhammad, I., Javeed, T., Khan, A. and Huo, X. 2021. Yield Gap Analysis of Major Food Crops in Pakistan: Prospects for Food Security. *Environ. Sci. Pollut. Res.*, **28**(7): 7994-8011.
44. Köninger, J., Lugato, E., Panagos, P., Kochupillai, M., Orgiazzi, A. and Briones, M. J., 2021. Manure Management and Soil Biodiversity: Towards More Sustainable Food Systems in the EU. *Agric. Syst.*, **194**: 103251.
45. Kopittke, P. M., Menzies, N. W., Wang, P., McKenna, B. A. and Lombi, E. 2019. Soil and the Intensification of Agriculture for Global Food Security. *Environ. Int.*, **132**: p.105078.
46. Kremen, C., 2020. Ecological Intensification and Diversification Approaches to Maintain Biodiversity, Ecosystem Services, and Food Production in a Changing World. *Emerg. Top. Life Sci.*, **4**(2): 229-240.
47. Lanz, B., Dietz, S., and Swanson, T. 2018. The Expansion of Modern Agriculture and Global Biodiversity Decline: An Integrated Assessment. *Ecol. Econ.*, **144**: 260-277.
48. Lu, H., Xie, H., Lv, T., and Yao, G., 2019. Determinants of Cultivated Land Recuperation in Ecologically Damaged Areas in China. *Land Use Policy*, **81**: 160-166.
49. Macedo, I., Terra, J.A., Siri-Prieto, G., Velazco, J.I. and Carrasco-Letelier, L., 2021. Rice-Pasture Agroecosystem Intensification Affects Energy Use Efficiency. *J. Clean. Prod.*, **278**: 123771.
50. Maulu, S., Hasimuna, O. J., Haambiya, L. H., Monde, C., Musuka, C. G., Makorwa, T. H., Munganga, B. P., Phiri, K. J. and Nsekanabo, J. D. 2021. Climate Change

- Effects on Aquaculture Production: Sustainability Implications, Mitigation, and Adaptations. *Front. Sustain. Food Syst.*, **5**: 609097.
51. Ministry of Agriculture-Jahad. 2016. *Agricultural Statistics*. Vol. 2, Ministry of Agriculture-Jahad Press, The Islamic Republic of Iran.
 52. Moll, R. H., Kamprath, E. J. and Jackson, W. A. 1982. Analysis and Interpretation of Factors Which Contribute to the Efficiency of Nitrogen Utilization. *Agron. J.*, **74**(3): 562-564.
 53. Morales, F., Ancin, M., Fakhet, D., González-Torralba, J., Gámez, A.L., Seminario, A., Soba, D., Ben Mariem, S., Garriga, M. and Aranjuelo, I. 2020. Photosynthetic Metabolism under Stressful Growth Conditions as a Base for Crop Breeding and Yield Improvement. *Plants*, **9**(1): 88.
 54. Muchero, W., Sondreli, K. L., Chen, J. G., Urbanowicz, B. R., Zhang, J. and Singan, V. 2018. Association Mapping, Transcriptomics, and Transient Expression Identify Candidate Genes Mediating Plant-Pathogen Interactions in A Tree. *PNAS*, **115**(45): 11573-11578.
 55. Nassiri Mahallati, M., Koocheki, A. 2017. Trend Analysis of Nitrogen Use and Productivity in Wheat (*Triticum aestivum* L.) Production Systems of Iran. *J. Agroecol.*, **9**(2): 360-378.
 56. Nehbandani, A., Soltani, A., Rahemi-Karlzaki, A., Dadras, A., Noubakhsh, F. 2021. Determination of Soybean Yield Gap and Potential Production in Iran Using Modeling Approach and GIS. *J. Integr. Agr.*, **20**(2): 395-407.
 57. Neumann, K., Verburg, P. H., Stehfest, E. and Müller, C. 2010. The Yield Gap of Global Grain Production: A Spatial Analysis. *Agr. Syst.*, **103**(5): 316-326.
 58. Pardo, A., Rolo, V., Carrascosa, A., Gonzalez-Bornay, G. and Moreno, G. 2023. Management Linked to Ecological Intensification Supports Insect Pollinators in Iberian Wood-Pastures. *Landsc. Ecol.*, **38**: 3389–3403.
 59. Parvizi, K., and Asadian, A. R. 2017. Effect of Defoliation Timing on Tuber Yield, Quality, and Storage Capability of Two Potato (*Solanum tuberosum* L.) Cultivars. *Iran. J. Plant Sci.*, **19**(3): 181-194.
 60. Pfiffner, L., Cahenzli, F., Steinemann, B., Jamar, L., Bjørn, M. C., Porcel, M., Tasin, M., Telfser, J., Kelderer, M., Lisek, J. and Sigsgaard, L. 2019. Design, Implementation, and Management of Perennial Flower Strips to Promote Functional Agrobiodiversity in Organic Apple Orchards: A Pan-European Study. *Agric. Ecosyst. Environ.*, **278**: 61-71.
 61. Rahman, K. M. and Zhang, D. 2018. Effects of Fertilizer Broadcasting on the Excessive Use of Inorganic Fertilizers and Environmental Sustainability. *Sustain. Sci.*, **10**(3): 759.
 62. Rasmussen, L.V., Coolsaet, B., Martin, A., Mertz, O., Pascual, U., Corbera, E., Dawson, N., Fisher, J. A., Franks, P., Ryan, C. M. 2018. Social-Ecological Outcomes of Agricultural Intensification. *Nat. Sustain.*, **1**(6): 275–282.
 63. Ramankutty, N., Mehrabi, Z., Waha, K., Jarvis, L., Kremen, C., Herrero, M. and Rieseberg, L. H. 2018. Trends in Global Agricultural Land Use: Implications for Environmental Health and Food Security. *Annu. Rev. Plant Biol.*, **69**: 789-815.
 64. Ray, D. K., Gerber, J. S., MacDonald, G. K. and West, P. C. 2015 Climate Variation Explains A Third of Global Crop Yield Variability. *Nat. Commun.*, **6**(1): 1-9.
 65. Raven, P. H. and Wagner, D. L. 2021. Agricultural Intensification and Climate Change are Rapidly Decreasing Insect Biodiversity. *PNAS*, **118**(2): 2002548117.
 66. Ryu, M.-H., Zhang, J., Toth, T., Khokhani, D., Geddes, B. A., Mus, F., Garcia-Costas, A., Peters, J. W., Pool, P. S., Ane, J. M., and Voigt, C. A. 2020. Control of Nitrogen Fixation in Bacteria That Associate With Cereals. *Nat. Microbiol.*, **5**(2): 314–330.
 67. Schmidt, R., Gravuer, K., Bossange, A. V., Mitchell, J. and Scow, K. 2018. Long-Term Use of Cover Crops and No-Till Shift Soil Microbial Community Life Strategies in



- Agricultural Soil. *Plos One*, **13**(2): 0192953.
68. Sharma, L. K. and Bali, S. K. 2018. A Review of Methods to Improve Nitrogen Use Efficiency in Agriculture. *Sustain. Sci.*, **10**(1): 51-74.
69. Silva, J.V., Reidsma, P., Baudron, F., Laborte, A. G., Giller, K. E. and van Ittersum, M. K. 2021. How Sustainable Is Sustainable Intensification? Assessing Yield Gaps at Field and Farm Level across the Globe. *Glob. Food Secur.*, **30**: 100552.
70. Silva, J. V., Pede, V. O., Radanielson, A. M., Kodama, W., Duarte, A., de Guia, A. H., Malabayabas, A. J. B., Pustika, A. B., Argosubekti, N., Vithoonjit, D. and Hieu, P. T. M., 2022. Revisiting Yield Gaps and the Scope for Sustainable Intensification for Irrigated Lowland Rice in Southeast Asia. *Agric. Syst.*, **198**: 103383.
71. Skaf, L., Buonocore, E., Dumontet, S., Capone, R. and Franzese, P. P. 2019. Food Security and Sustainable Agriculture in Lebanon: An Environmental Accounting Framework. *J. Clean. Prod.*, **209**: 1025-1032.
72. Stomph, T., Dordas, C., Baranger, A., de Rijk, J., Dong, B., Evers, J., Gu, C., Li, L., Simon, J., Jensen, E. S., Jensen, Q. and Wang, V. D. W. 2020. Designing Intercrops for High Yield, Yield Stability and Efficient Use Of Resources: Are There Principles? *Adv. Agron.*, **160**(1): 1-50.
73. Swarbreck, S. M., Wang, M., Wang, Y., Kindred, D., Sylvester-Bradley, R., Shi, W., Bentley, A. R. and Griffiths, H. 2019. A Roadmap for Lowering Crop Nitrogen Requirement. *Trends Plant Sci.*, **24**(10): 892-904.
74. Timsina, J. 2018. Can Organic Sources of Nutrients Increase Crop Yields to Meet Global Food Demand? *J. Agron.*, **8**(10): 214.
75. Tscharntke, T., Grass, I., Wanger, T.C., Westphal, C. and Batáry, P. 2021. Beyond Organic Farming—Harnessing Biodiversity-Friendly Landscapes. *Tree*, **36**(10): 919-930.
76. Urruty, N., Tailliez-Lefebvre, D. and Huyghe, C. 2016. Stability, Robustness, Vulnerability and Resilience of Agricultural Systems. A Review. *Agron. Sustain. Dev.*, **36**(1): 1-15.
77. Udawatta, R. P., Rankoth, L. M. and Jose, S. 2019. Agroforestry and Biodiversity. *Sustainability*, **11**(10): 2879.
78. Verón, S. R., Paruelo, J. M. and Slafer, G. A. 2004. Inter Annual Variability of Wheat Yield in The Argentine Pampas During The 20th Century. *Agr. Ecosyst. Environ.*, **103**(1): 177-190.
79. Victorio, R. G., Moreno, U., Black Jr, C. C. 1986. Growth, Partitioning, and Harvest Index of Tuber-Bearing Solanum Genotypes Grown in Two Contrasting Peruvian Environments. *Plant Physiol.*, **82**(1): 103-108.
80. Vidal, E. A., Alvarez, J. M., Araus, V., Riveras, E., Brooks, M. D., Krouk, G., Ruffel, S., Lejay, L., Carwford, N. M., Coruzzi, G. M. and Gutierrez, R. A. 2020. Nitrate in 2020: Thirty Years From Transport to Signaling Networks. *Plant Cell*, **32**(7): 2094-2119.
81. Wang, Y., Zhang, Y., Zhang, R., Li, J., Zhang, M., Zhou, S. and Wang, Z. 2018. Reduced Irrigation Increases the Water Use Efficiency and Productivity of Winter Wheat-Summer Maize Rotation on the North China Plain. *Sci. Total Environ.*, **618**: 112-120.
82. Wan, N. F., Chen, J., Ji, X. Y., Chacón-Labella, J., Zhang, H., Fan, N. N., Jiang, J. X. and Li, B. 2019a. Co-Culture of Multiple Aquatic Species Enhances Vegetable Production in Coastal Shanghai. *J. Clean. Prod.*, **241**: 118419.
83. Wan, N. F., Li, S. X., Li, T., Cavalieri, A., Weiner, J., Zheng, X. Q., Ji, X. Y., Zhang, J. Q., Zhang, H. L., Zhang, H. and Bai, N. L. 2019b. Ecological Intensification of Rice Production through Rice-Fish Co-Culture. *J. Clean. Prod.*, **234**: 1002-1012.
84. Wan, N. F., Zheng, X. R., Fu, L.W., Kiær, L. P., Zhang, Z., Chaplin-Kramer, R., Dainese, M., Tan, J., Qiu, S. Y., Hu, Y. Q. and Tian, W. D. 2020a. Global Synthesis of Effects of Plant Species Diversity on Trophic Groups and Interactions. *Nat. Plants*, **6**(5): 503-510.
85. Wan, N. F., Su, H., Cavalieri, A., Brack, B., Wang, J. Y., Weiner, J., Fan, N. N., Ji, X.

- Y. and Jiang, J. X. 2020b. Multispecies Co-Culture Promotes The Ecological Intensification of Vegetable Production. *J. Clean. Prod.*, **257**: 120851.
86. Xie, H., Huang, Y., Chen, Q., Zhang, Y. and Wu, Q. 2019. Prospects for Agricultural Sustainable Intensification: A Review of Research. *Land*, **8(11)**: 157.
87. Yang, H., Wu, G., Mo, P., Chen, S., Wang, S., Xiao, Y., ang Ma, H., Wen, T., Guo, X. and Fan, G. 2020. The Combined Effects of Maize Straw Mulch and No-Tillage on Grain Yield and Water and Nitrogen Use Efficiency of Dry-Land Winter Wheat (*Triticum aestivum* L.). *Soil Till. Res.*, **197**: 104485.
88. Zytynska, S. E. and Meyer, S. T., 2019. Effects of Biodiversity in Agricultural Landscapes on the Protective Microbiome of Insects— A Review. *Entomol. Exp. Appl.*, **167(1)**: 2-13.
89. Zhang, Z., Gao, S. and Chu, C. 2020. Improvement of Nutrient Use Efficiency in Rice: Current Toolbox and Future Perspectives. *Theor. Appl. Genet.*, **133(5)**: 1365–1384.
90. Zhao, J., Wang, Y., Zhao, M., Wang, K., Li, S., Gao, Z., Shi, X. and Chu, Q., 2023. Prospects for Soybean Production Increase by Closing Yield Gaps in the Northeast Farming Region, China. *Field Crops Res.*, **293**: 108843.

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

ف. معلم بنهنگی، پ. رضوانی مقدم، س. خرمدل، و م. نصیری محلاتی

چکیده

اولین گام برای دستیابی به پایداری و فشرده سازی اکولوژیکی 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 (۱۳۹۵-۱۳۸۰) پرداخته است. بر اساس نتایج حاصل از پژوهش، عملکرد سیب زمینی سالانه ۰/۲۸ تن در هکتار در سال افزایش یافت. این مطالعه نشان داد که میانگین عملکرد پتانسیل سیب زمینی به روش فائو ۶۴ تن در هکتار محاسبه شد. همچنین، عملکرد پتانسیل در طول دوره مورد مطالعه افزایش معنی داری نداشت. میانگین خلاء عملکرد سیب زمینی ۳۲/۴۴ 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 ۱۱۰ کیلوگرم غده به ازای هر کیلوگرم کود نیتروژن به ۷۰ کیلوگرم کاهش یافت. با توجه به روند کاهشی) NUpE کارایی جذب نیتروژن) و) NUE کارایی مصرف نیتروژن) در طول سال های مورد مطالعه، خلاء NUE عامل اصلی افزایش مصرف نیتروژن، افزایش فشرده سازی و کاهش پایداری در سیستم های 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.