

1 **Agroecological intensification of potato (*Solanum tuberosum* L.) cultivation for**
2 **sustainable and increased productivity in the Torbat-e Heydariyeh region of**
3 **Iran**
4

Fatemeh Moallem Banhangi¹, Parviz Rezvani Moghaddam^{1*}, Surur Khorramdel¹, and Mehdi Nassiri Mahallati¹

5
6 **Abstract**

7 The first step to achieving ecological sustainability and intensification in agricultural systems is to
8 have a comprehensive agroecological analysis of agricultural systems. This research analyzed the
9 agroecological ecosystem of potato cultivation in the Torbat-e Heydariyeh region of Iran over
10 fifteen years (2001-2016). Based on the results, potato yield increased by 0.28 kg.ha⁻¹.yr⁻¹. The
11 study showed that the average potential yield of potato was calculated by the FAO method to be
12 64 t.ha⁻¹; also, the potential yield did not increase significantly during the study period. The average
13 yield gap of potato was calculated to be 32.44 t.ha⁻¹. Also, with increasing yield, the yield gap
14 showed a decreasing trend. The ecosystems experienced a steady rise in intensification, and the
15 stability has decreased. It was observed that even though nitrogen fertilizer application was
16 increased, its efficiency dropped from 110 kg tuber per kg of nitrogen fertilizer to 70 kg. Due to
17 the decreasing trend of NUpE (Nitrogen uptake efficiency) and NUE (Nitrogen use efficiency)
18 during the studied years, the NUE gap was the main factor in increasing nitrogen consumption,
19 increasing intensification, and reducing stability in the studied systems. Therefore, changing the
20 management method to increase the efficiency of nitrogen consumption can be suggested as the
21 first step for moving towards ecological intensification and improving the sustainability of potato
22 growing systems.

23 **Keywords:** Fertilizer, Nitrogen use efficiency, Potential yield, Stability, Yield gap.
24

25 **1. Introduction**

26 Currently, most agricultural ecosystems face higher rates of chemical application and
27 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

28 Intensification has played the most crucial role in shaping the structure of agriculture over the past
29 decades in different parts of the world. According to the European Commission, intensification
30 consists of increasing agricultural inputs per hectare of arable land, increasing production per unit
31 area, or increasing production in exchange for agricultural labor (Commission European, 2017). It
32 is only possible to produce more agricultural products by increasing the intensification of
33 conventional agricultural systems without significant environmental damage (Rasmussen *et al.*,
34 2018).

35 Agricultural intensification has been recognized as one of the main reasons for biodiversity loss
36 and related decline in ecosystem functioning due to the conversion of natural habitats into
37 monoculture farming areas (Wan *et al.*, 2019a). Agricultural intensification has given rise to
38 negative impacts on ecosystems, such as a reduction in the diversity of pollinating insects (Raven
39 and Wagner., 2021), a reduction in biological control (Cusumano *et al.*, 2020), and damage to the
40 environment from the excessive use of synthetic pesticides and mineral fertilizers (Wan *et al.*,
41 2020a). In addition, at the same time as climate change increases, due to the increase in the use of
42 chemical pesticides, herbicides, and poisons, the yield stability of many agricultural systems has
43 decreased and has led to an increase in the yield gap (Silva *et al.*, 2021; Silva *et al.*, 2022; Maulu
44 *et al.*, 2021). Therefore, developing sustainable alternatives to reduce chemical fertilizers,
45 pesticides, herbicides, and other agricultural inputs is one of the main challenges. Achieving this
46 goal is challenging without reducing production and overall yield as the demand for agricultural
47 products steadily increases (Blösch *et al.*, 2023).

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

55 "Ecological intensification" is defined as using natural processes to replace human-produced inputs
56 like pesticides and fertilizers while maintaining or increasing food production per unit area (Gaitán-
57 Cremaschi *et al.*, 2020; Pardo *et al.*, 2023 Wan *et al.*, 2020b). Ecological intensification through
58 agricultural diversification, where additional crops are grown in space and time, and more robust

59 provision of ecosystem services, such as enhanced soil fertility and natural pest and weed control,
60 has been advocated as a sustainable approach to reducing yield gaps (Silva *et al.*, 2022).

61 The FAO defines ecological intensification as the maximum initial production per unit area without
62 compromising the system's ability to maintain production capacity (FAO, 2009).

63 The concept of "ecological intensification" has been promoted to redesign agroecosystems based
64 on the increased use of ecological processes and biodiversity, using resources more efficiently, and
65 decreasing anthropogenic inputs (Wan *et al.*, 2019b). Ecological intensification emphasizes
66 reducing the difference between potential and actual yield by increasing input use efficiency
67 (Macedo *et al.*, 2021). Increasing biodiversity is one of the most important solutions for ecological
68 intensification (Kremen, 2020). Increasing agrobiodiversity through methods such as mixed culture
69 (Joshi *et al.*, 2020), the use of cover plants (Abdalla *et al.*, 2019), and rice-fish co-culture (Wan *et al.*,
70 2019b). Agrobiodiversity can influence and provide numerous ecosystem services in terrestrial
71 ecosystems (Pfißner *et al.*, 2019).

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

79 Over the past decade, there has been a growing body of literature concerning yield gap, stability,
80 and sustainability in different parts of Iran (Nehbandani *et al.*, 2021; Dehkordi *et al.*, 2020; Alasti
81 *et al.*, 2020; Dadrasi *et al.*, 2020). Most of these studies have been carried out over larger scales
82 and neglected local variations in crop yield, which necessitates local scale studies (Neumann *et al.*,
83 2010). Before creating a general plan to move towards ecological intensification, studies are needed
84 to determine the overall picture of the ecological characteristics of the agricultural systems of each
85 region according to the type of farming system. Such studies will provide a scientific framework
86 for similar research to continue in other ecosystems at the local scale. Based on this data, the best
87 program can be designed and implemented to move towards ecological intensification for each
88 region. Potato (*Solanum tuberosum* L.) is a significant food crop cultivated in 79% of the world,

89 with an annual production of 370.4 million tons (Gustavsen 2021; FAO, 2019). Potato ranks fourth
90 after wheat, rice, and corn (FAO, 2019) and requires comprehensive agroecological studies.
91 Therefore, with the formulation of the best agricultural program to move towards ecological
92 intensification in the potato cultivation systems in the Torbat-e Heydariyeh region, northeastern
93 Iran, this research uses a systematic method to conduct an ecological analysis of potato agricultural
94 systems. The results of this study have determined the general picture of the ecological features of
95 potato cultivation systems in the Torbat-e Heydariyeh region, and using this information, the best
96 program can be designed and implemented to move towards ecological intensification.

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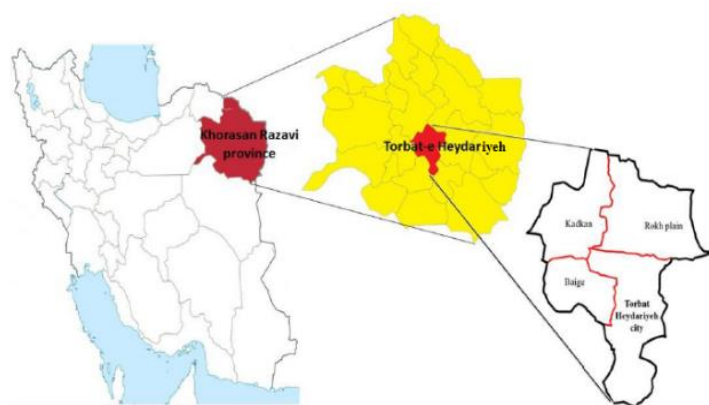
98 **2. Materials and Methods**

99 **2.1. Data collection**

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

103 Torbat-e Heydariyeh is located between latitudes $35^{\circ}.2798'$ N and longitudes $59^{\circ}.2161'$ E,
104 encompassing an area of about 3900 km², and the average altitude of the city is 1333 m above sea
105 level (Akbari *et al.*, 2018).

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



110
111 **Figure 1.** Study location.
112

113 2.2. Potential yield estimation by the FAO method

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

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

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

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

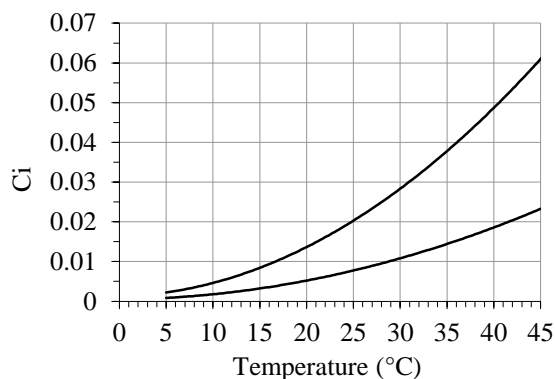


Figure 2. Relation between the coefficient of maintenance respiration (C_i in Equations 5 and 6) and average growth period temperature for 1) non-leguminous species and b) leguminous species. Source: Versteeg and van Keulen, 1986.

122 The GPHOT value is obtainable from Figure 3 for each level of daily solar radiation. Here, the
123 GPHOT value is estimated based on the maximum light-saturated leaf photosynthesis rate (F_g , kg
124 $\text{CO}_2\cdot\text{ha}^{-1}\cdot\text{hr}^{-1}$) and requires prior knowledge of F_g 's value. In addition to plant species, leaf
125 photosynthesis is also a function of temperature. F_g is the maximum photosynthetic capacity of a
126 single leaf at different temperatures. Figure 4 illustrates F_g values for different groups of crops in
127 a wide range of temperatures.

128 According to this figure, F_g for potato approaches $40 \text{ kg CO}_2 \cdot \text{ha}^{-1} \cdot \text{hr}^{-1}$ at 20°C . Referring to the
 129 values in the right section of Figure 3, the GPHOT value for potatoes under the daily radiation of
 130 $20 \text{ MJ} \cdot \text{m}^{-2}$ is equivalent to $420 \text{ kg glucose} \cdot \text{ha}^{-1} \cdot \text{hr}^{-1}$.

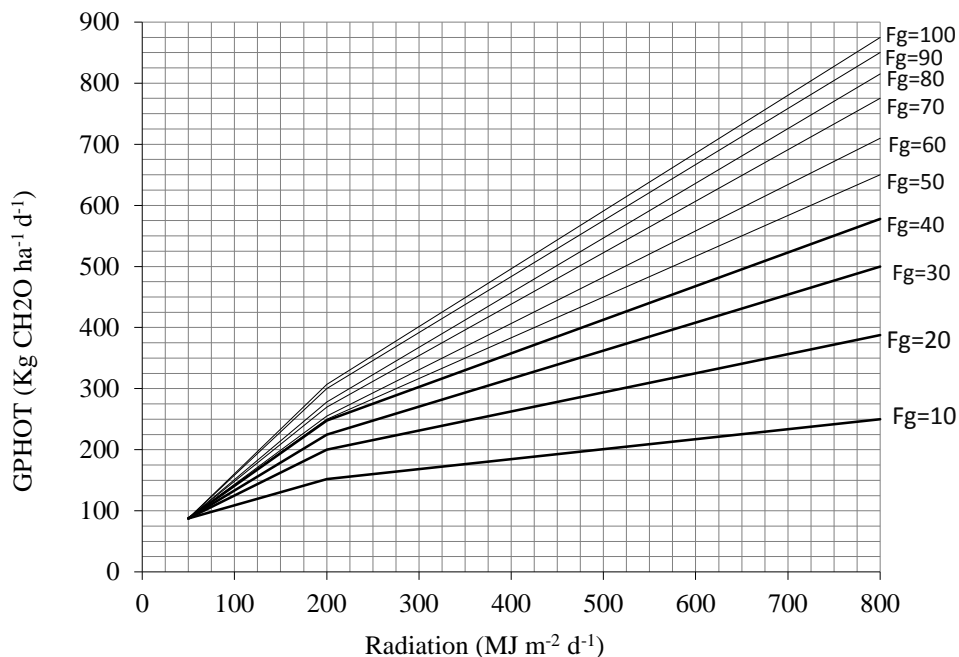


Figure 3. Daily gross photosynthesis rate (GPHOT, $\text{kg CH}_2\text{O ha}^{-1}\text{d}^{-1}$) for closed canopy (linear growth period) as a function of maximum photosynthesis rate of the single leaf at light saturation (F_g , $\text{kg CO}_2 \text{ ha}^{-1}\text{h}^{-1}$) and daily radiation ($\text{MJ m}^{-2}\text{d}^{-1}$) in latitudes between 0-40. Source: Versteeg and van Keulen, 1986.

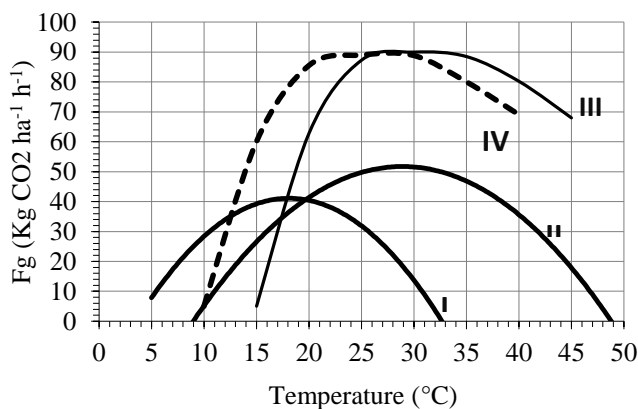


Figure 4. Relation between maximum photosynthesis rate of the single leaf at light saturation (F_g , $\text{kg CO}_2 \text{ ha}^{-1}\text{h}^{-1}$) and temperature in 4 groups of crop species: I) Temperate C3 species (wheat, barley, potatoes, sugar beet), II) Warm climate C3 species (rice, soybean, cotton, cassava), III) C4 species (corn, sorghum, millet, sugarcane) 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.

131 Eventually, once the total dry matter production (TDM, kg.ha⁻¹) is calculated, annual crop yield
132 could be estimated based on the harvest index (harvest index was assumed to be 80% for potato
133 (Victorio *et al.*, 1986). Next, the results obtained from the FAO method were validated using the
134 Root Mean Square Error (RMSE) test. RMSE is the standard deviation of the residuals (prediction
135 errors) (Eq. 3). Here, values lower than 10% indicate an excellent simulation, while values between
136 10-20% indicate simulations to be satisfactory, between 20-30% moderate, and more than 30%
137 poor (Jamieson *et al.*, 1991).

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

138 **2.3. Estimating yield gap**

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

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

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

142

143 **2.4. Intensification**

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

146

147 **2.4.1. Intensification evaluation based on inputs:**

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

153

154 **2.4.2. Intensification evaluation based on outputs:**

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

158

159 2.5. Yield stability evaluation

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

161

162 2.5.1. Evaluation of yield stability based on regression residuals:

163 The yield regression equation for different crops over consecutive years indicates yield variation.

164 The residuals of this regression equation point to the differences between annual actual and
165 predicted yields and hence reflect the impact of environmental conditions (climate) on yield and
166 can be considered an indicator of yield stability.

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

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

$$\text{Two-segment} \quad Y = a + bx \quad \text{if } x \leq c$$
$$\text{linear} \quad Y = a + bc + d(x-c) \quad \text{if } x < c \quad (6)$$

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

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

185 **2.5.2. Evaluation of yield stability based on the coefficient of variation:**

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

191
192 **2.6. Nitrogen use efficiency**
193 Nitrogen uptake efficiency (NUpE) as the amount of nitrogen uptake by the plant per unit of
194 nitrogen in the soil and nitrogen use efficiency (NUE), including economic yield per kg of nitrogen
195 used, was obtained from Equations 8 and 9 (Moll *et al.*, 1982):

$$196 \quad NUpE = \frac{N_u}{N_f} \times 100 \quad (8)$$

$$197 \quad NUE = \frac{GY_{fertilized} - GY_{unfertilized}}{N_f} \quad (9)$$

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

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

209 In Equation 9, GY fertilized is the economic yield with nitrogen consumption, and GY unfertilized
210 is the economic yield without nitrogen consumption. In practice, unfertilized yield is obtained from
211 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.

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

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

215
 216 **3. Results and Discussion**

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

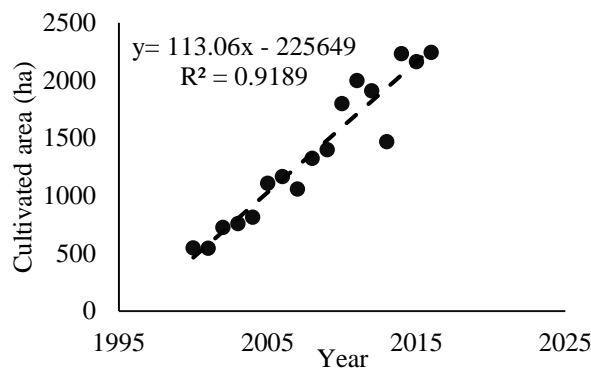


Figure 5. Variations in potato cultivation area in the Torbat-e Heydariyeh.

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

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

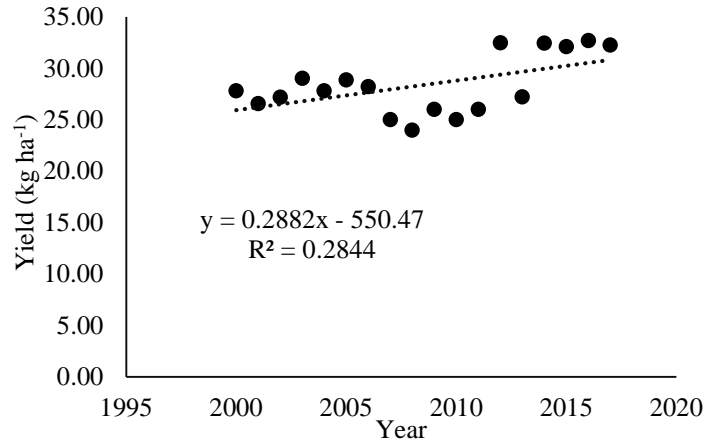


Figure 6. Potato yield variations in the Torbat-e Heydariyeh.

228 The studied period is characterized by $0.28 \text{ kg} \cdot \text{ha}^{-1} \cdot \text{yr}^{-1}$ increase in potato yield. Parvizi and Asadian
 229 (2017) reported an increase in average yield from $27 \text{ t} \cdot \text{ha}^{-1}$ in 2006 to more than $30 \text{ t} \cdot \text{ha}^{-1}$ in 2013.
 230 Increasing the yield can be achieved with the help of plant breeding methods and improving the
 231 potential yield in the region (Morales *et al.*, 2020) or with the help of crop management and
 232 improving the actual yield and reducing the yield gap in the region (Deng *et al.*, 2019). Potential
 233 yield refers to the yield of a compatible crop in an environment with no restriction of water and
 234 nutrients and effective control of pests, diseases, and weeds. The crop growth rate in potential yield
 235 is determined solely by environmental factors and crop characteristics (Folberth *et al.*, 2020).
 236 Potential yield over the study period was estimated using the FAO method. The results obtained
 237 from the FAO method were validated by determining using RMSE. RMSE was calculated to be
 238 15%, indicating a good model performance. The results suggested a relatively constant actual
 239 potato yield ($65 \text{ t} \cdot \text{ha}^{-1}$) over the studied period; the trend did not increase significantly (Figure 7).

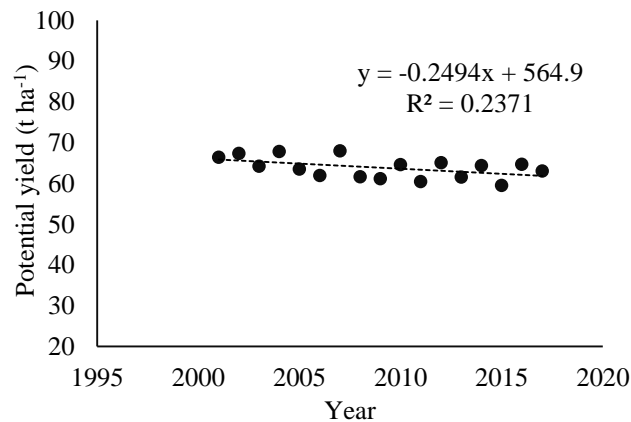


Figure 7. Potential yield of potato obtained via the FAO method.

240 The increase in potato yield during the study period in the region was not a result of the increase
 241 in the potential yield of potato. Hence, the trend of the yield gap in potato was examined. The
 242 difference between the potential yield and the maximum actual yield obtained in a region is called
 243 the yield gap (Zhao et al., 2023).
 244 The highest practical potential yield for the area was determined from the recorded values (leading
 245 farmers), datasets of the Department of Agriculture, results of the research projects conducted
 246 under potential environmental conditions, and direct interviews with the staff of the relative
 247 organizations. The data was split into quartiles, and the average of the third quartile was considered
 248 the highest practical potential yield for the region (Personal communication). The results suggested
 249 a 20-38% yield gap for potatoes in the region (Figure 8). However, the data indicated a decreasing
 250 trend in the yield gap (Figure 8).

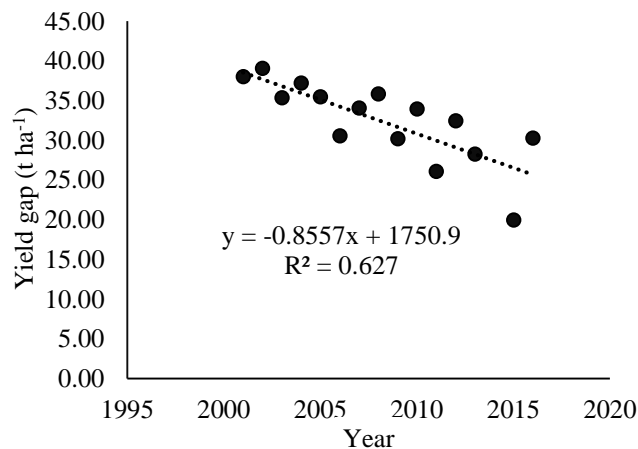


Figure 8. Potato yield gap trend in the Torbat-e Heydariyeh region.

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

257 In this study, intensification was evaluated based on input and output parameters. The cost index
 258 was used for the significant chemical fertilizers (urea and ammonium superphosphate) based on
 259 the input parameters in the first method. By calculating the consumption costs per hectare per year,
 260 a 15-year cost-based intensification trend was plotted. All prices were calculated in US dollars
 261 (www.indexmundi.com). According to the results, the intensification rate increased from \$ 44 per

262 hectare in 2001 to \$ 120 per hectare in 2016 (Figure 9). The increase in intensification in 2007
 263 resulted from the sudden upsurge in the global urea fertilizer price (www.indexmundi.com).
 264 Providing farmers with fertilizers, pesticides, and seeds at low prices has been one of the supportive
 265 policies of the Iranian government since 1977, pursuing the aim of self-sufficiency in the
 266 agricultural sector. Studies show that the average urea consumption in Iran is 38% higher than the
 267 global average (Rahman and Zhang, 2018), leading to the intensification of agricultural systems
 268 and, therefore, environmental consequences and lower input use efficiency.

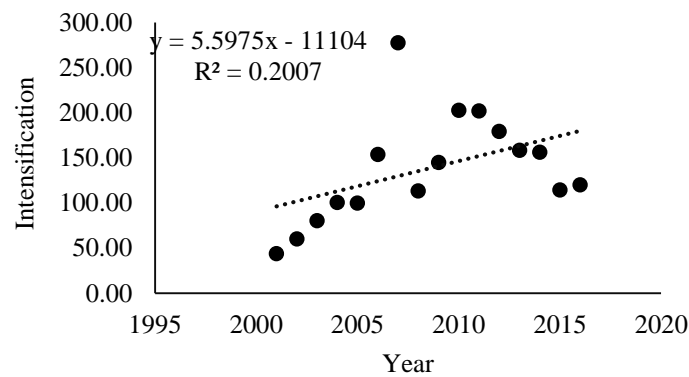


Figure 9. Changes in the intensification of potato cultivation systems in the Torbat-e Heydariyeh region.

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

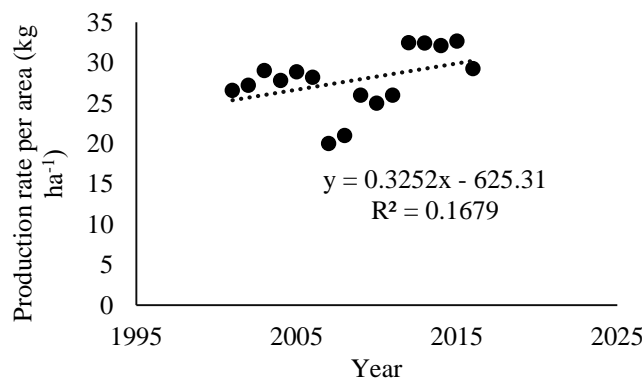


Figure 10. Changes in potato production per unit area in the Torbat-e Heydariyeh region.

275

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

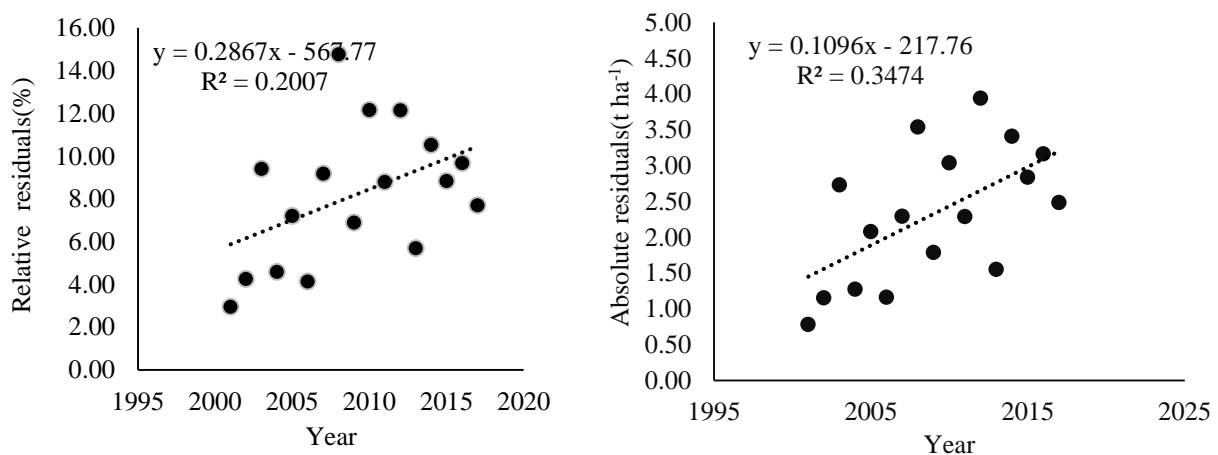


Figure 11. Changes in absolute and relative residual values of potato yield in the Torbat-e Heydariyeh region.

293

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

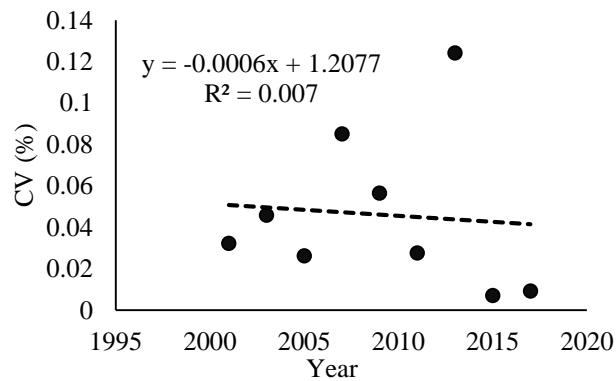


Figure 12. Changes in the coefficient of variation of potato yield in the Torbat-e Heydariyeh region.

301 The findings also suggested a growing trend in the absolute value of the crop yield residuals over
 302 the years while adding to the area under potato cultivation. These results suggest that increasing
 303 the cultivation area could lower crop yield stability in the region (Figure 13).
 304

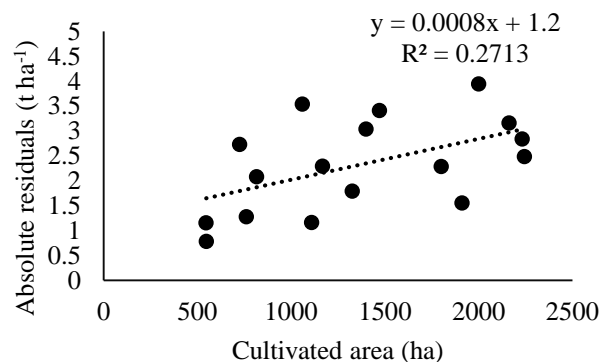


Figure 13. The absolute value of the potato yield residuals as a function of cultivation area.

305 A decrease in yield stability indicates that the increase in potato yield in the study area will not be
 306 sustainable in the long term. Considering that the Torbat-e Heydariyeh is one of Iran's leading
 307

308 centers of potato production, failure to change these ecosystems' management style in the long term
 309 will lead to a sharp decline in production and yield .One of the most important factors affecting
 310 crop yield stability is fertilizer use efficiency (Stomph *et al.*, 2020). The industrial production of
 311 chemical fertilizers, especially nitrogen fertilizers, was one of the most significant technological
 312 advances in agriculture in the 20th century (Guo *et al.*, 2021). Nitrogen fertilizers' contribution to
 313 improving yield has been reported to be between 30 to 50% (Ahmed *et al.*, 2017).

314 According to the reports, global nitrogen fertilizer consumption increased from 13.5 million tons
 315 in 1962 to 189.5 million tons in 2019 (FAO, 2019). On the other hand, 50% of the energy used in
 316 agricultural production is related to the industrial production of nitrogen fertilizers (Kaab *et al.*,
 317 2019). **The increase in chemical fertilizer use decreased efficiency and stability (Haroon *et al.*,
 318 2019; Chen *et al.*, 2018b).**

319 Improving nitrogen use efficiency is a crucial strategy to promote sustainable agricultural systems,
 320 which leads to maximum yield in exchange for minimum inputs and nitrogen wastage (Dimkpa *et al.*,
 321 2020).

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

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

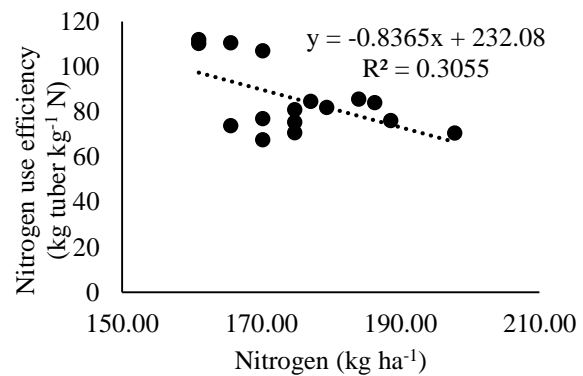
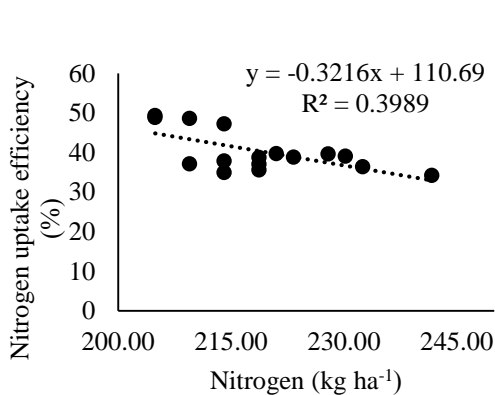


Figure 14. Nitrogen uptake efficiency of potatoes in the Torbat-e Heydariyeh region. **Figure 15.** Nitrogen use efficiency of potatoes in the Torbat-e Heydariyeh region.

326
 327 During the study, increasing nitrogen fertilizer application lowered nitrogen use efficiency from
 328 110 kg of tubers per kg of nitrogen to 70 kg (Figure 15). Sharma and Bali (2018) examined the

329 methods of improving nitrogen use efficiency and stated that increasing nitrogen fertilizers'
330 application could lower nitrogen use efficiency.

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

336 Generally, the possible actions to increase nitrogen use efficiency to increase ecological
337 intensification can be divided into biotechnological breeding and agricultural-management
338 measures. One possible measure to increase nitrogen use efficiency is to genetically modify plants
339 to improve the efficiency of resource consumption, particularly nitrogen consumption. (Aseel *et*
340 *al.*, 2019; Vidal *et al.*, 2020; Zhang *et al.*, 2020). Using crops that absorb nitrogen more efficiently
341 is a more straightforward way to increase nitrogen use efficiency (Swarbreck *et al.*, 2019). Utilizing
342 these crops will reduce the consumption of food elements by using a higher efficiency of
343 consumption and increasing ecological intensification. In a further method of moving towards
344 ecological intensification, plants are genetically manipulated to reduce their immune systems and
345 increase microbial colonization in their roots. This work aims to create and increase symbiosis
346 between nitrogen-fixing microorganisms and non-legume plants, which allows non-legume plants
347 to benefit from symbiosis (Ryu *et al.*, 2020; Muchero *et al.*, 2018). Among the possible measures
348 in the second group (management and agricultural measures), some biological solutions may be
349 used for maximizing resource efficiency, reducing intensification, and increasing ecological
350 intensification (Bargaz *et al.*, 2018). Some of these strategies include adding a nitrogen-fixing
351 cover crop in rotation, manipulating soil microbial populations in a controlled manner, and using
352 nitrogen-fixing bacteria in agricultural ecosystems (Schmidt *et al.*, 2018; Igiehon and Babalola,
353 2018). Crop rotation is one of the other effective management methods to increase nitrogen use
354 efficiency and ecological intensification. Using legumes or other cover plants can increase nitrogen
355 use efficiency by reducing the need to use chemical fertilizers and preventing nitrate runoff (Chen
356 *et al.*, 2018). In addition, the absorption of washed water and the reuse of water from agricultural
357 drainage systems can help to recover nutrients lost in runoff (Ashu and Lee, 2019). Using
358 conservation tillage methods with their effect on the microbial population, the amount of biomass
359 in the soil, and resource use efficiency can help increase ecological intensification in agricultural

360 ecosystems (Alijani *et al.*, 2019). Based on different results, nitrogen use efficiency increased in
361 the conservation tillage and no-tillage systems (Yang *et al.*, 2020; Jug *et al.*, 2019). Studies have
362 shown that maintaining plant residues by adjusting soil temperature and increasing biodiversity
363 affects nitrogen absorption efficiency. The reason for this is the plant's greater access to nitrogen
364 due to the gradual release of plant residues and chemical fertilizers (Wang *et al.*, 2018).

365 366 **Conclusions**

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

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

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665 **چکیده**

666 اولین گام برای دستیابی به پایداری و فشرده‌سازی اکولوژیکی در سیستم های کشاورزی، داشتن یک تحلیل جامع
667 زراعی از سیستم های کشاورزی است. این تحقیق به بررسی اکوسیستم های زراعی کشت سیب زمینی در منطقه
668 تربت حیدریه ایران طی پانزده سال (1380-1395) پرداخته است. بر اساس نتایج حاصل از پژوهش، عملکرد سیب
669 زمینی سالانه 0/28 کیلوگرم در هکتار در سال افزایش یافت. این مطالعه نشان داد که میانگین عملکرد پتانسیل سیب
670 زمینی به روش فائو 64 تن در هکتار محاسبه شد. همچنین، عملکرد پتانسیل در طول دوره مورد مطالعه افزایش
671 معنی داری نداشت. میانگین خلاء عملکرد سیب زمینی 32/44 تن در هکتار محاسبه شد. همچنین با افزایش عملکرد،
672 خلاء عملکرد روند کاهشی نشان داد. در طی دوره‌ی مطالعه، در سیستم‌های مورد بررسی فشرده‌سازی افزایش
673 و ثبات سیستم‌ها کاهش یافت. نتایج نشان داد که با وجود افزایش مصرف کود نیتروژن، کارایی آن از 110 کیلوگرم
674 غده به ازای هر کیلوگرم کود نیتروژن به 70 کیلوگرم کاهش یافت. با توجه به روند کاهشی (NUpE) کارایی جذب
675 نیتروژن) و (NUE کارایی مصرف نیتروژن) در طول سال‌های مورد مطالعه، خلاء NUE عامل اصلی افزایش
676 مصرف نیتروژن، افزایش فشرده‌سازی و کاهش پایداری در سیستم‌های مورد مطالعه بود. بنابراین تغییر روش
677 مدیریت برای افزایش راندمان مصرف نیتروژن را می‌توان به عنوان اولین قدم برای حرکت به سمت فشرده‌سازی
678 اکولوژیکی و بهبود پایداری سیستم های کشت سیب زمینی پیشنهاد کرد.
679 واژه‌های کلیدی: پایداری، خلاء عملکرد، عملکرد پتانسیل، کود، کارایی مصرف نیتروژن.