

An approach to increase sustainability in agricultural systems; An agroecological analysis of the wheat and sugar beet ecosystems

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1 **An approach to increase sustainability in agricultural systems; An agroecological analysis of the**
2 **wheat and sugar beet ecosystems**

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13
14
15 **Abstract**

16 The goal of this study was to undertake a detailed investigation of the agroecological state of the wheat and sugar beet
17 ecosystems on a local scale. From 2001 to 2016, a set of the most critical agroecological indicators of wheat and sugar
18 beet farming systems in the Torbat-e Heydarieh region, northeast of Iran, were studied. Potential yield calculations
19 using both FAO and modified FAO methodologies revealed that potential yield was nearly consistent for both
20 ecosystems over the research period in the region. The extent of the yield gap for both habitats decreased. The study
21 of the regional yield factor revealed that improving the management system resulted in higher actual yield and thus a
22 smaller yield gap in both ecosystems. In both ecosystems, there was a reduction in yield stability. The rate of nitrogen
23 uptake efficiency, nitrogen utilization efficiency, and nitrogen use efficiency (NUE) all decreased during the studied
24 years in the region. According to the findings, the primary cause of the increase in nitrogen consumption, growing
25 intensification, and decreasing stability in the analyzed systems appears to be a deficiency of NUE and its downward

26 trend. As a result, planning and altering management methods focusing on enhancing NUE may be proposed as the
27 first step toward boosting sustainability in the Torbat-e Heydarieh wheat and sugar beet agroecosystems.

28 **Keywords:** data analysis, efficiency, intensification, regional yield factor, stability.

29

30 1. Introduction

31 Prior to the invention of agriculture, the world's population was no more than 6 million people. By the year 1000, this
32 figure had risen to almost 250 million, and by the year 2000, it had risen to 6.1 billion. The world's population is
33 expected to increase to 9.8 billion by 2050. As a result, to attain food security in the world, food production must grow
34 by almost 70% between 2005 and 2050. (Kopittke et al., 2019). Increasing food production is accomplished by either
35 increasing the area under cultivation or extending production per unit area (Pellegrini and Fernández, 2018); however,
36 increasing the area under cultivation has proved impossible in recent years. Governments have been forced to raise
37 output per unit area. The growth in agricultural productivity was accompanied by an increase in the usage of
38 agricultural technology and the consumption of chemical inputs (Pellegrini and Fernández, 2018). In other words, off-
39 farm input consumption rose in many agroecosystems.

40 Most agricultural systems eventually became more intensive as a result. Various studies reveal that intensification has
41 played an essential role in altering agriculture in various world regions during the last few decades (Knapp and van
42 der Heijden, 2018; Rose et al., 2019). Increased intensification and productivity in agroecosystems have had a variety
43 of effects. Among the implications of intensification include environmental degradation (Jones et al., 2013), a
44 reduction in the sustainability of agroecosystems (Knapp and van der Heijden, 2018), and food insecurity (Kopittke et
45 al., 2019). Three criteria measure food security: "availability and access to food," "economic viability of food purchase
46 and selection," and "ensuring healthy and sustainable food production and provision." (Schindler et al., 2017) Because
47 one of the essential foundations of food security is production sustainability (Tscharntke et al., 2012), lowering the
48 sustainability of agricultural systems will jeopardize food security (Berry et al., 2015). As a result, even though yield
49 per unit area has improved in most crops (Liliane and Charles, 2020), concerns about food security for the world's
50 rising population remain unchanged. Given the preceding, guaranteeing food security in the future will necessitate a
51 shift in management approaches to boost output, agroecosystem sustainability, and stability and reduce the
52 environmental harm caused by agriculture (Bommarco et al., 2018). The complete Evaluation and analysis of
53 agroecological features according to their type is a prerequisite for establishing an optimal management technique.
54 After analyzing the present state of each region's shared ecosystems, the optimal strategy for boosting production
55 stability must be devised and implemented. Given the large-scale geographical variety in yield, the study of ecological
56 factors and the presentation of large-scale management strategies are ineffective, necessitating more specific
57 investigations at the local small-scale (Neumann et al., 2010). Assessing the future state of wheat and sugar beet
58 agricultural output is critical owing to their relevance in global nutrition. According to statistics, wheat has the biggest
59 harvest of any crop in Iran (Ministry of Agriculture-Jahad, 2016).

60 On the other hand, Iran is the 11th most significant producer of sugar beet globally, with 5.5 million tons produced
61 and around 111,000 hectares planted, and the third-largest in the Middle East (FAO, 2018). As a result, a thorough
62 agroecological investigation of wheat and sugar beet appears necessary. As a result, this research aims to use a

63 systematic method to conduct an ecological analysis of wheat and sugar beet agricultural systems in the Torbat-e
64 Heydariéh region of northeastern Iran.

65 2. Materials and Methods

66 2.1. Data collection

67 In order to study the wheat and sugar beet cultivation systems in the Torbat-e Heydariyeh region, data were collected
68 on the area under cultivation, yield, and input consumption (including water, nitrogen, and phosphorus fertilizers)
69 from 2001 to 2016. Data was acquired from the Ministry of Agriculture (Ministry of Agriculture-Jahad, 2016) and other
70 related organizations and direct interviews with the farmers. In addition, data on climatic parameters (including daily
71 minimum and maximum temperatures, precipitation, and sunny hours) were collected from the Torbat-e Heydariyeh
72 meteorological station.

73 <<Figure 1>>

74 <<Figure 2>>

75 2.2. Trend analysis

76 Based on the obtained information, the following items calculated are to achieve a systemic approach in the
77 ecological analysis of wheat and sugar beet cultivation systems in the Torbat-e Heydariyeh region.

78 2.3. Potential yield estimation by the FAO method

79
80 The method proposed by FAO for agroecological crop zoning (FAO, 1978; FAO, 1981) requires calculating the growth
81 rate in the linear phase (LGR, kg.ha⁻¹.day⁻¹) and total dry matter production (TDM, kg.ha⁻¹) under potential
82 environmental conditions via eq. 1 and 2:

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

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

83
84 GPHOT is the average rate of gross canopy photosynthesis (kg glucose.ha⁻¹.day⁻¹), *p* is the length of the growing
85 period (120 days for wheat (Versteeg and Van Keulen, 1986) and 238 days for sugar beet), and *C_i* is the maintenance
86 respiration coefficient. The constant values are related to growth respiration and adjusted maintenance respiration
87 coefficient. *C_i* is a function of temperature, and its value for legume and non-legume species can be obtained from
88 Figure 3.

89 <<Figure 3>>

90 The GPHOT value is obtainable from Figure 4 for each level of daily solar radiation. The GPHOT value is estimated
91 based on the maximum light-saturated leaf photosynthesis rate (*F_g*, kg CO₂. ha⁻¹.hr⁻¹) and requires prior knowledge of
92 *F_g*'s value. In addition to plant species, leaf photosynthesis is also a function of temperature. *F_g* is the maximum

93 photosynthetic capacity of a single leaf at different temperatures. Figure 5 illustrates Fg values for different groups of
94 crops in a wide range of temperatures.

95 <<Figure 4>>

96 <<Figure 5>>

97 Eventually, once the total dry matter production (TDM, kg.ha⁻¹) is calculated, annual crop yield could be estimated
98 based on the harvest index (harvest index was assumed to be 45% for Wheat (Dai et al., 2016) and 75% for Sugar
99 beet (Sanghera et al., 2016). Finally, wheat grain yield was calculated based on 12% moisture and sugar beet yield
100 based on 25% dry matter (Abdollahian-Noghabi et al., 2013).

101 2.4 Potential yield estimation by the modified FAO method

102 This method is a summary model of Versteeg and van Keulen (Versteeg and van Keulen, 1986) and a modified FAO
103 method. For total dry matter calculation (TDM, kg.ha⁻¹), the growth period length, average temperature, and average
104 daily solar radiation (MJ m⁻² d⁻¹) are required during the linear growth period.

105 Total dry matter (TDM, Kg/h) Calculated with equation 3.

$$106 \quad \text{TDM} = 2500 + \text{DM}_L + \text{DM}_F \quad \text{Eq 3}$$

107 Where 2500 dry matter is produced in the exponential stage (kg.ha⁻¹), DMF and DML are produced in the linear and
108 final stages (kg.ha⁻¹), respectively. Therefore, the value of TDM is obtained by equating DML and DMF from Equation
109 4:

$$110 \quad \text{TDM} = 2500 + (0.4 \times p \times \text{LGR}) + (0.15 \times p \times 0.5 \times \text{LGR}) \quad \text{Eq 4}$$

111 LGR is the linear growth rate (kg.ha⁻¹.day), and p is the length of the growth period (120 for wheat and 238 for sugar
112 beet). Coefficients of 0.4 and 0.15 show the share of the linear growth period and final growth of the total growth
113 period. The growth rate in the final stage is considered to be half LGR.

114 GPHOT is the average rate of gross canopy photosynthesis, which was previously described in the FAO method. Cm
115 is the maintenance respiration rate (kg of glucose per kg of dry matter) during the linear growth period. This coefficient
116 is a function of temperature during the period of linear growth, and in terms of respiration rate of different products is
117 obtained from Figure 6.

118 <<Figure 6>>

119 For Figure 6, the value of Rm for each product must first be specified in Table 1: (Versteeg and van Keulen, 1986).

120 The Rm for wheat equals 0.015, and for sugar beet, it equals 0.01 kg of glucose per kg of dry matter per day. Figure
121 6 shows the Cm of wheat from curve two and the sugar beet from curve 1.

122 << Table 1>>

123 Ec is the conversion ratio of glucose to dry matter, and its value for different products is presented in Table 1. The
124 value of this coefficient was considered 0.70 for wheat and 0.75 for sugar beet.

125 CL is the correction factor for the complete closure of the canopy during linear growth. Its value in LAI = 5 is equal
126 to one, in LAI = 4 is equal to 0.9, and in LAI = 3 is 0.7, and its average for use in Equation 3 is 0.95. Cp is the

127 maintenance correction coefficient for conditions where the length of the linear growth period is more or less than the
 128 standard length of this period (46 days). The value of this coefficient is obtained from Figure 7.

129 <<Figure7>>

130 Finally, similar to the previous method, the total amount of dry matter produced (TDM, kg.ha⁻¹) was multiplied by the
 131 harvest index, the amount of dry matter yield per year was calculated, and the final yield was calculated by calculating
 132 the percentage of moisture. The box plot in Mini Tab.17 software was used to calculate the highest practical potential
 133 yield for the area. For this purpose, the recorded values (leading farmers), datasets of the Ministry of Agriculture,
 134 results of the research projects conducted under potential environmental conditions, and direct interviews with the
 135 staff of the relative organizations were collected.

136 The data was split into quartiles, and the mean of the third quartiles and the maximum yield were considered the
 137 maximum yield observed in the region. The maximum actual performance obtained from this method approximates
 138 the potential performance observed ([Van Ittersum et al., 2013](#)).

139 Finally, the results obtained from the FAO and modified FAO method were validated using the potential
 140 performance observed and Root Mean Square Error (RMSE) test (Eq. 5) ([Jamieson et al., 1991](#)).

$$RMSE(\%) = \sqrt{\frac{\sum_{i=1}^n (P_i - O_i)^2}{n}} \times \frac{100}{O} \quad (Eq\ 5)$$

141
 142 2.5. Estimating yield gap

$YG_i = YF_i - Yai$	(Eq 6)
---------------------	--------

144
 145 The difference between the potential and actual yields is called the yield gap ([Akintayo et al., 2011](#)). The yield gap is
 146 measured as the difference between potential yields (YFi) and observed actual yield (Yai) (Eq. 6).

147 2.6. Regional Yield Factor (RYF)

148 The regional yield factor (RYF) was investigated as a criterion for measuring management method improvement over
 149 time, which was calculated from Equation 7.

$$RYF = Y_a / Y_p \quad (Eq\ 7)$$

150
 151 Ya is the actual performance in this equation, and Yp is the potential performance. The value of the regional
 152 performance coefficient varies between zero and one and indicates the level of development of the production system
 153 in a region. With proper management of water, food, pests, diseases, weeds, and optimization of crop operations such
 154 as density and planting date, the actual yield will be closer to the potential, and RYF will go to one, which indicates
 155 the development of the production system in an area. By managing the limiting factors and reducing factors of
 156 production. By managing the limiting factors of production, the actual performance value can be brought closer to the
 157 potential performance ([Badsar et al., 2017](#)).

158 2.7. Intensification This study evaluated two different wheat and sugar beet cultivation methods intensifying in the Torbat-e
 159 Heydariyeh.

160 This study evaluated two different methods of wheat and sugar beet cultivation intensifying in the Torbat-e Heydariyeh

161 *2.7.1. Intensification evaluation based on inputs:*

162 The cost index was used for farm inputs, including common chemical fertilizers including urea fertilizer (46%
163 nitrogen) and triple superphosphate (46% P₂O₅), to calculate intensification. Finally, once consumption cost was
164 calculated per hectare, intensification was evaluated based on the incurred cost index (Commission European, 2017).
165 The average price of each input per year was obtained from www.indexmundi.com web side's website to calculate
166 each input cost per year.

167 *2.7.2. Intensification evaluation based on outputs*

168 Physiologically, output intensification increases production per unit area and time (Hunt, 2000). Therefore, wheat and
169 sugar beet production per year per unit area was calculated and plotted for the studied period to calculate the
170 intensification.

171 *2.8. Yield stability evaluation*

172 Wheat and sugar beet yield stability were evaluated via two different methods in this study:

173 *2.8.1. Evaluation of yield stability based on regression residuals:*

174 The yield regression equation for different crops over consecutive years indicates yield variation over time. The
175 residuals of this regression equation point to the differences between annual actual and predicted yields and hence
176 reflect the impact of environmental conditions (climate) on yield and can be thought of as an indicator of yield stability.
177 In order to accurately calculate the regression residuals, it is mandatory to primarily obtain a suitable regression model
178 to describe crop yield variations. A low R-squared value indicates more significant regression residuals, which
179 unreliable results. In light of this fact, we used linear regression (Eq. 8), two-segment (Eq. 9), and three-segment linear
180 regression (Eq. 10) models to explain the crop yield trend of each crop (Calderini and Slafer, 1999; Verón et al., 2004)
181 and the best model was selected based on the highest coefficient of determination and normality of their residual
182 distribution (Calderini and Slafer, 1999).

Linear $Y = a + bx$ (Eq 8)

Two-segment linear $Y = a + bx$ if $x \leq c$
 $Y = a + bc + d(x-c)$ if $x < c$ (Eq 9)

Three-segment linear $Y = a + bx$ if $x \leq c$
 $Y = a + bc + d(x-c)$ if $e \leq x < c$ (Eq 10)
 $Y = a + bc + d(e-c) + f(x-c)$ if $x < e$

183
184 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
185 segment, c is the year in which the first turning point occurs, d is the rate of yield increase during the second linear

186 segment, e is the year in which the second turning point of the trend occurs, and f is the rate of yield increase during
 187 the third linear segment (Calderini and Slafer, 1998; Verón et al., 2004). After model selection, the regression model has
 188 calculated the difference between actual and predicted performance as the yield residuals. Since only the changes in
 189 absolute yield magnitude are essential for stability assessment, the absolute magnitude of all yield residuals was
 190 calculated. Next, the yield residuals were divided by the actual yield to obtain the relative yield residuals to ascertain
 191 the ratio between yield residuals to actual yield in a given year (Calderini and Slafer, 1998). Finally, by plotting the
 192 relative yield residuals over time, each product's trend of yield stability was obtained.

193 *2.8.2. Evaluation of yield stability based on the coefficient of variation:*

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

198 *2.9. Nitrogen use efficiency*

199 Nitrogen use efficiency (NUE) is the economic yield per kg of nitrogen obtained from Equations 13 (Moll et al., 1982).
 200 Nitrogen use efficiency is segmented into two components: Nitrogen uptake efficiency (NUpE) and Nitrogen
 201 utilization efficiency (NUtE) (Congreves et al., 2021, Moll et al., 1982). Nitrogen uptake efficiency (NUpE) is the
 202 proportion of nitrogen harvested by the plant per unit of nitrogen in the soil (Weih et al., 2018) (Eq. 11). Nitrogen
 203 utilization efficiency (NUtE) kg Economic yield per kg of nitrogen absorbed, also known as the physiological
 204 efficiency of nitrogen (Yang et al., 2021) (Eq. 12).

$$NUpE = \frac{N_u}{N_f} \times 100 \quad \text{Eq 11}$$

$$NUtE = \frac{GY_{fertilized} - GY_{unfertilized}}{Nu} \quad \text{Eq 12}$$

$$NUE = \frac{GY_{fertilized} - GY_{unfertilized}}{N_f} \quad \text{Eq 13}$$

205 N_u is the amount of nitrogen uptake by the plant ($\text{kg}\cdot\text{ha}^{-1}$), and N_f is the soil nitrogen amount (nitrogen fertilizer
 206 applied and soil and seed nitrogen content). The annual dry matter yield was initially calculated by dividing the
 207 economic yield by the harvest index (harvest index was assumed to be 45% for wheat (Dai et al., 2016) and 75% for
 208 sugar beet (Sanghera et al., 2016) to estimate the nitrogen amount absorbed by the plant (in this study economic yield
 209 in sugar beet means the yield of sugarbeet root). The difference between dry matter yield and economic yield will

210 determine the annual biomass yield. Finally, plant nitrogen uptake was obtained from the sum of nitrogen from the
211 economic product (the product of nitrogen percentage and economic yield) and biomass nitrogen content (the product
212 of biomass nitrogen content (%) and biomass yield).

213 In Eq.13, GY fertilized is the economic yield with nitrogen consumption, and GY unfertilized is the economic yield
214 without nitrogen consumption. In practice, unfertilized yield is obtained from the control treatment. Since we did not
215 include any control treatment in this study, the regression line intercept (Eq. 14) between economic yield (GY) and
216 the corresponding amount of fertilizer applied (Nf) was considered as GY unfertilized (Cassman et al., 2002)

$$GY = a + PNP \times N_f \quad \text{Eq 14}$$

217 The intercept of this line gives the GY unfertilized in Eq.14, and the slope provides the ratio of economic yield per
218 unit of fertilizer used, showing the average partial nitrogen productivity (kg of grain per kg of nitrogen consumed)
219 (Cassman, 2001).

220 **3. Results and discussion**

221 A survey of the area under cultivation of wheat and sugar beet in the Torbat-e Heydariyeh region revealed that the
222 area under cultivation decreased between 2001 and 2016. (Figure 8). During this time, roughly 1095 ha of wheat and
223 408 ha of sugar beet crop area were decreased every year. A study of changes in the area under wheat and sugar beet
224 agriculture across the country revealed a 13 and 29 percent decrease from 2001 to 2016 (Ministry of Agriculture-
225 Jihad, 2001; Ministry of Agriculture-Jahad, 2016).

226 <<Figure 8>>
227

228 Unlike the area under cultivation, variations in wheat and sugar beet yield in Torbat-e Heydarieh from 2011 to 2016
229 showed an upward tendency (Figure9). According to this model, the average yearly growth of wheat and sugar beet
230 yield was 0.15 and 0.94 t.ha⁻¹, respectively. During the research period, the average wheat and sugar beet yield was
231 calculated to be 3.28 and 28.5 t.ha⁻¹, respectively (Figure9).

232 <<Figure 9>>

233 Despite a decline in the area under wheat and sugar beet cultivation, the production of both crops grew by 115 and 59
234 percent, respectively. Crop breeding or agricultural management can enhance yield in a given region (Cobb et al.,
235 2013). Crop breeding methods improve potential yield (Brummer et al., 2011), whereas farming methods improve
236 actual yield by modifying management practices and closing the yield gap (Senapati and Semenov, 2020). The
237 potential yield in the research period for both crops was calculated using both FAO and modified FAO methodologies.
238 The RMSE error was used to validate the findings obtained from both approaches. The% RMSE value for both FAO
239 and modified FAO methods indicated excellent model prediction, and forecasting by the FAO method was better than
240 modified FAO(Figure10)

241 <<Figure 10>>

242 The results revealed that the average wheat yield was 6.7 and 6.45 t.ha⁻¹ using the FAO and modified FAO
243 methodologies, respectively (Figure 11). Similarly, the average yield of sugar beet was 87 t.ha⁻¹ by FAO and 81.3 t.ha⁻¹
244 by modified FAO methods, respectively (Figure 12). During the study period, the trend of potential yield with both
245 approaches did not alter dramatically but fell with a very moderate slope.

246 <<Figure 11>>

247 <<Figure 12>>

248 According to current research, potential yield variations have not been significant throughout the years (Xu et al.,
249 2020). In this context, Aggarwal and Kalra (1994) discovered 2 Mg variations in wheat potential yield by evaluating
250 annual changes in potential wheat yield in India.

251 The minor drop in potential yield over 15 years for both crops implies that the cause for the increase in reported
252 average yield values has little to do with potential yield increases but rather with agronomic factor improvements.
253 Agronomic factors boost actual yields and close production gaps using farm management strategies (Senapati and
254 Semenov, 2020). As a result, we examined the wheat and sugar beet yield gaps change from 2001 to 2016. The results
255 revealed a yield gap of 1 to 4.3 t.ha⁻¹ for wheat in the studied area (Figure 13). During the examined years, there was
256 a declining trend in the wheat yield gap, which was filled by 6 kg.ha⁻¹ (Figure 13). The average yield gap percentage
257 of the wheat ecosystem was 44 percent (Figure 13).

258 <<Figure13>>

259 The sugar beet yield gap averaged 35 t.ha⁻¹ over the research period, with a declining trend (Figure 14). During the
260 research period, the percentage of sugar beet yield gap ranged from 53 to 69 %, with an average of 63 % (Figure 14).

261 <<Figure14>>

262 During the research period, wheat and sugar beet had the highest and lowest yield gaps of 56 percent and 37 percent,
263 respectively, compared to the region's potential yield. Compared to the initial years of the survey, the yield gap
264 between wheat and sugar beet improved by 38% and 13%, respectively, in the study's final years (2016). According
265 to several authors, the yield gap is affected by yearly weather conditions, and it is lower in years with lower production
266 potential than in years with higher potential (Aggarwal and Kalra, 1994; Caldiz et al., 2001; Abeledo et al., 2008 and
267 Senapati and Semenov, 2020).

268 Given the above, the minor decrease in potential yield for both crops had only a minor impact on closing the yield
269 gap. The major cause for this drop was an increase in actual yield in the region. As a result, a considerable rise in
270 actual yield, combined with a minor fall in potential yield, has narrowed the yield gap. Gobbett et al. (2017) also
271 suggested that enhanced management can bridge current crop production and achievable yield. The regional yield
272 factor (RYF) was investigated as a criterion for measuring management method improvement over time. According
273 to the findings, the average yield coefficient of the Torbat-e Heydarieh region from 2001 to 2016 was 0.52 for wheat
274 and 0.33 for sugar beet (Figure 15). The regional yield factor for both ecosystems has risen over time. Wheat and
275 sugar beet regional yields increased by 132 % and 69 %, respectively, from 2001 to 2016. (Figure 15).

276 <<Figure15>>

277 The rate of increase of the regional yield factor in the wheat ecosystem was faster than in the sugar beet ecosystem,
278 indicating that management activities were progressing. Given that the regional yield factor represents farmers'

279 management operations in each region (Lobell et al., 2009), raising this factor demonstrated an improvement in
280 management operations in the analyzed systems. Several studies show that in recent years, agricultural ecosystem
281 management operations have shifted toward intensive management and the use of various technologies, including
282 intensive tillage, chemical fertilizers, pesticides, and chemical herbicides (Beckmann et al., 2019), resulting in
283 increased intensification in agroecosystems (Thomson et al., 2019; Cassman and Grassini, 2020; Jhariya et al., 2021).
284 In order to analyze the trajectory of intensification changes, the quantity of intensification for two crops of wheat and
285 sugar beet in the Torbat-e Heydariyeh region was studied for 15 years. The magnitude of intensification was
286 determined in this study utilizing two methods (based on input and output parameters). According to the findings, the
287 level of intensification grew from 2001 to 2016 for both wheat and sugar beet ecosystems (Figure 16). According to
288 the findings, the rate of intensification in the wheat system grew from \$ 47.5 in 2001 to \$ 127.5 per hectare in 2016.
289 Prices for sugar beets increased from \$47.5 in 2001 to \$139 per hectare in 2016. (Figure 16). Sugar beet intensification
290 increased faster during the research period than wheat, with 192 % vs. 168 % for sugarbeet and wheat. The pattern of
291 intensification changes in both agroecosystems revealed the spike rising trend from 2001 to 2007, followed by a
292 decreasing trend from 2007 to 2016. (Figure 16).

293

294 <<Figure16>>

295 The substantial increase in intensification in 2007 was caused by a sudden spike in the worldwide price of urea (Figure
296 17) and triple superphosphate (Figure 18) fertilizers (www.indexmundi.com).

297 <<Figure17>>

298 <<Figure18>>

299 Despite a declining trend in intensification beginning in 2007, usage of both urea and triple superphosphate fertilizers
300 in the analyzed products increased (Figure19). The rationale for the declining trend of intensification in this study
301 from 2007 onwards was solely due to a fall in worldwide costs of these inputs, whereas usage of chemical fertilizers
302 had grown.

303 <<Figure19>>

304 Chemical fertilizers are becoming more popular in the region. According to studies, the average urea consumption in
305 Iran is 38% greater than the global average (Dihim Fard and Nazari, 2015). In this regard, Carvalho (2006) indicated
306 that pesticides in developing and developed countries are moving; on the contrary route, developing countries are
307 using more pesticides, and developed countries are reducing their consumption. In other words, researchers have
308 linked the rapid rise in pesticide use in developing countries to the importance of food supply over environmental
309 concerns (Wilson and Otsuki, 2004; Hedlund et al., 2020, Zhang, 2018). Hunt (2000) suggests that because the
310 objective of agriculture is production, output indices in agricultural systems give a more accurate and better
311 approximation of land intensification. According to the European Union's Joint Commission (Commission European,
312 2012), intensification is the increase in agricultural inputs per hectare of arable land, which results in increased output

313 per unit area. In this regard, a study of intensification based on the output of both ecosystems in the Torbat-e
314 Heydariyeh region revealed that The area required to produce one ton per product decreased over time. (Figure 20).

315 <<Figure20>>

316 One of the most significant intensification purposes is to enhance yield and, consequently, production. Increased
317 intensification is measured by increasing production per unit area and time in a region ([Beckmann et al., 2019](#)).

318 The results in the research area for both the wheat and sugar beet ecosystems demonstrate a decline in yield gap and
319 an increase in production throughout the analyzed years. Increased yield and decreased yield gap seen in this area will
320 enhance food security if accompanied by stable yield ([Farooq et al., 2019](#)). In other words, raising output must be
321 done so that agricultural ecosystems can sustain production potential over time ([Altieri, 2002](#)). Yield stability is an
322 essential component of sustainable production in agricultural ecosystems ([Knapp and van der Heijden, 2018](#)). Stability
323 is a measure of year-over-year yield variations in a region that reveals the strength of yield fluctuations in short-term
324 environmental changes ([Nielsen and Vigil, 2018](#)). According to the study's findings, there has been a rather substantial
325 dispersion in the absolute residual yield of wheat and sugar beet during the previous 15 years, owing to yield
326 fluctuations.

327 The absolute residual changes in wheat yield in the Torbat-e Heydariyeh region until 2013 had a decreasing trend, and
328 the last three years of the study had an increasing trend. In other words, the rate of performance stability increased
329 until 2013, but in the last three years, the rate of performance stability in the region decreased (Figure 21).

330 <<Figure21>>

331 <<Figure22>>

332 The relative residual yield analysis revealed that the stability of wheat farming systems in the Torbat-e Heydariyeh
333 region decreased from 2001 to 2013 but increased with a very moderate slope from 2013 to 2016. Examining the data
334 concerning the sugar beet ecosystem revealed that the dispersion rate of absolute regression values in sugar beet ranged
335 between 0.2 and 6.6 t.ha⁻¹, and the trend of changes in absolute regression values in sugar beet was growing (Figure
336 22). An examination of the trajectory of changes in the relative residues of sugar beet during the 15 years analyzed
337 revealed that the relative residual yield of sugar beet has grown by 21% per year, indicating that the crop is becoming
338 more unstable (Figure 22).

339 Overall, a comparison of the stability of the two ecosystems in Torbat-e Heydariyeh based on absolute and relative
340 residual yield revealed stability in wheat and sugar beet cultivation ecosystems, despite increased output throughout
341 the 15-year research period. As a result, the rate of this instability in sugar beet was more significant than in wheat
342 (Figure 21 and Figure 22). Calculating the coefficient of variation is another approach to yield stability study.

343 As a simple and widely used indicator, the coefficient of variation measures the standard deviation of yield relative to
344 the mean in different environments, periods, or years; thus, the higher the coefficient of change in yield, the greater
345 the volatility and, as a result, the greater yield instability ([Ray et al., 2015](#)). The coefficients change ranged for wheat,
346 and sugar beet yields from 3.3 to 18.9 % and 2.9 to 4.9 %, respectively, which indicated instability in both ecosystems
347 (Figure 21 and Figure 22). In sugar beet, dispersion occurred more rapidly than in wheat. In the study, the slope of the
348 trend of yield variation coefficient for wheat decreased initially. Subsequently, it increased in the last years of the
349 study and for sugar beet, which indicates the instability of sugar beet ecosystems has increased over time, and the
350 instability of wheat ecosystems has also increased in the last years of the study. (Figure 21 and Figure 22). Several

351 studies have found a negative link between agricultural productivity and stability ([Urruty et al., 2016](#); [Calderini and](#)
352 [Slafer, 1998](#); [Knapp and van der Heijden, 2018](#)). The instability of optimal yield in the studied ecosystems indicates
353 that the increase in yield observed in these ecosystems in the study area will not be sustainable in the long run. As a
354 result, failing to adapt the management approach of these ecosystems will result in a dramatic drop in productivity
355 and yield in the long run. The effectiveness of chemical fertilizer application is one of the most critical elements
356 influencing crop yield stability. The decline in the effectiveness of chemical fertilizer use over the previous few
357 decades has increased the use of these inputs, leading to greater instability in agricultural systems ([Chen et al., 2018](#)).
358 Therefore, improving nitrogen consumption efficiency is crucial in promoting sustainable agricultural systems with
359 the highest yield in exchange for minimum inputs and nitrogen loss ([Congreves et al., 2021](#)). Nitrogen use efficiency
360 (Equation 10) is divided into two components: Nitrogen uptake efficiency (NUpE) and Nitrogen utilization efficiency
361 (NUtE) ([Congreves et al., 2021](#), [Moll et al., 1982](#)). Both wheat and sugar beet crops had an average nitrogen uptake
362 efficiency of less than 52% during the study. Research shows that in intensive agricultural systems, more than 50% of
363 the nitrogen applied on the farm is not used by the plant ([Andarzian, 2019](#)). Because of the increased usage of chemical
364 fertilizers in both ecosystems (Figure 19), nitrogen uptake efficiency decreased over the study years with increasing
365 nitrogen fertilizer application in wheat and sugar beet (Figure 23 and Figure 24). According to our findings, the
366 declining trend in nitrogen uptake efficiency was more pronounced in sugar beet than in wheat (Figure 23 and Figure
367 24).

368 <<Figure23>>

369 <<Figure24>>

370 According to the findings, a rise in nitrogen consumption throughout the examined years resulted in decreased
371 kilograms of economic output generated per kilogram of nitrogen absorbed (efficiency of nitrogen use) in wheat and
372 sugar beet ecosystems. The results revealed that nitrogen use efficiency was reduced by 0.23 kg seed/kg N in wheat
373 and 0.72 kg root/kg in sugar beet for one kilogram of available plant nitrogen (total nitrogen in fertilizer and soil)
374 (Figure 23 and Figure 24).

375 **Discussion**

376 Providing enough and sustainable food for everyone is the only way to fulfill the world's rising population ([Knapp](#)
377 [and van der Heijden, 2018](#)). Therefore, a complete agroecological study of agroecosystems and their significant
378 ecological characteristics using the existing management approach in each region is required. Analyzing the
379 management scheme allows us to predict the future of the systems in terms of sustainability. The optimal strategy
380 might then be devised and followed to maximize output while advancing towards greater sustainability in each
381 ecosystem, if necessary, by keeping or modifying some management approaches.

382 A comprehensive agroecological investigation of wheat and sugar beet cultivation systems in the Torbat-e Heydarieh
383 region from 2001 to 2016 revealed that yields of both crops in the region are growing (Figure 9). The computation of
384 potential yield using the modified FAO and FAO methodologies revealed that the potential yield in the region was
385 nearly consistent over the research period for both ecosystems (Figure 11 and Figure 12). As a result, the reported
386 decrease in the yield gap in the region was attributed to an increase in actual yield in the tested systems (Figure 13 and
387 Figure 14). However, the study found an increase in the pace of intensification of wheat and sugar beet agricultural
388 systems over the studied years (Figures 16 and 20) and a loss in instability (Figure 21 and Figure 22). Reduced yield

389 stability indicated that the observed increase in yield in the research region would not be long-term sustainable. Given
390 the decreasing trend in NUE, NUpE, and NUtE for both ecosystems in the region during the studied years (Figure 23
391 and Figure 24), nitrogen consumption efficiency is the primary factor in increased nitrogen consumption
392 intensification and decreased stability. As a result, planning and adjusting management methods to boost nitrogen
393 consumption efficiency may be proposed as the initial step toward enhancing sustainability in wheat and sugar beet
394 production systems in the Torbat-e Heydarieh region. Many studies have shown that it is feasible to boost nitrogen
395 usage efficiency by 30 to 50 percent ([Hutchings et al., 2020](#); [Zhang et al., 2020](#); [Langholtz et al., 2021](#)). Among the
396 methods to improve nitrogen consumption management are: the optimal timing of nitrogen fertilizer application
397 ([Dimkpa et al., 2020](#); [Wallace et al., 2020](#)), determining the best way to apply nitrogen fertilizer to reduce consumption
398 losses ([Zhang et al., 2018](#)), such as spraying and using a drip irrigation system, deep fertilizer cultivation ([Wu et al.,
399 2021](#)), the use of biological mulches to prevent nitrogen wastage ([Yang et al., 2020](#)), and prioritizing the enhancement
400 of nitrogen use efficiency in plant breeding to produce seeds with higher efficiency ([Cormier et al., 2016](#); [van Bueren
401 and Struik, 2017](#)) and use of biological and native sources of nitrogen ([Sharma and Bali, 2017](#)). In addition to boosting
402 the sustainability of agricultural systems, these will enhance the economic efficiency of fertilizer consumption and
403 reduce consequent environmental damages.

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407 **Declarations**

408 **Conflict of interests:** The authors declare that they have no known competing financial interests.

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Table 1. Maintenance respiration rate (R_m , kg CH₂O kg DM⁻¹d⁻¹) and conversion efficiency (E_c , kg DM kg⁻¹ CH₂O) at reference temperature (20 and 30 °C for temperate and tropical species, respectively). Source: Versteeg, and van Keulen, 1986

Crop group	R_m	E_c
Root/tuber crops	0.010	0.75
Cereals	0.015	0.70
Protein-rich seed crops	0.025	0.65
Oil-rich seed crops	0.030	0.50

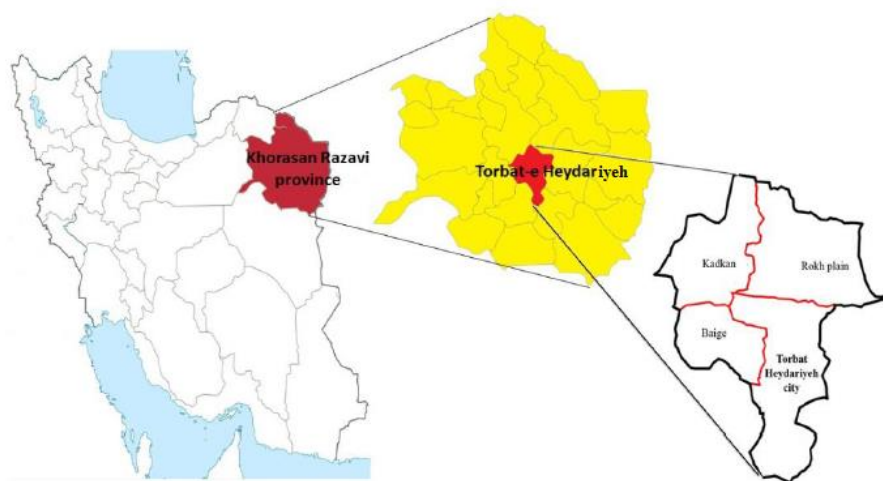


Figure 1. Study location

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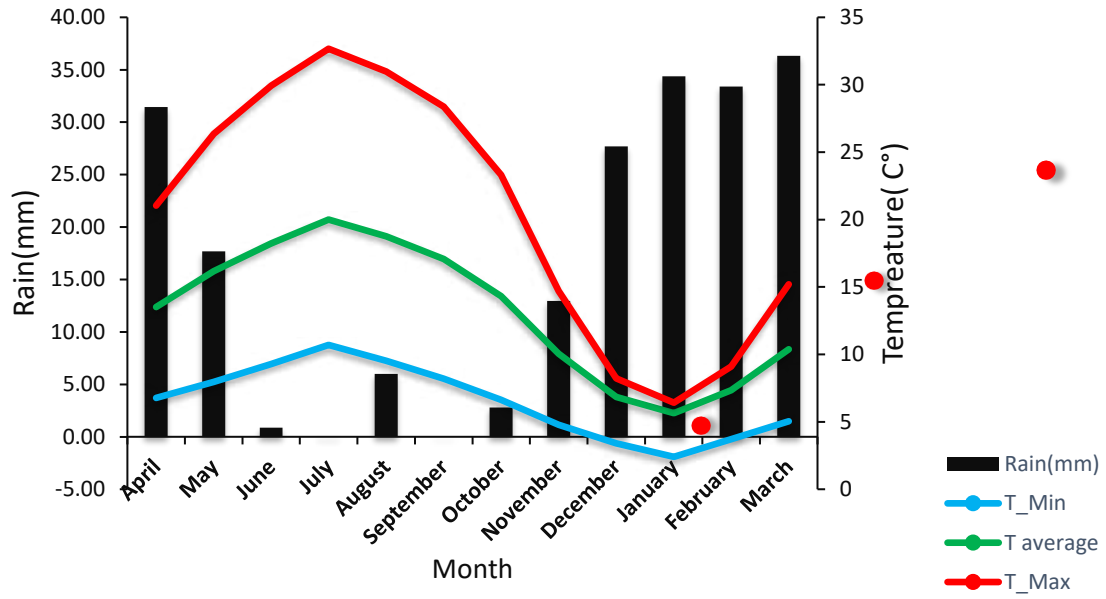


Figure 2. Trend of average temperature and precipitation in Torbat-e Heydariyeh during the experimental period

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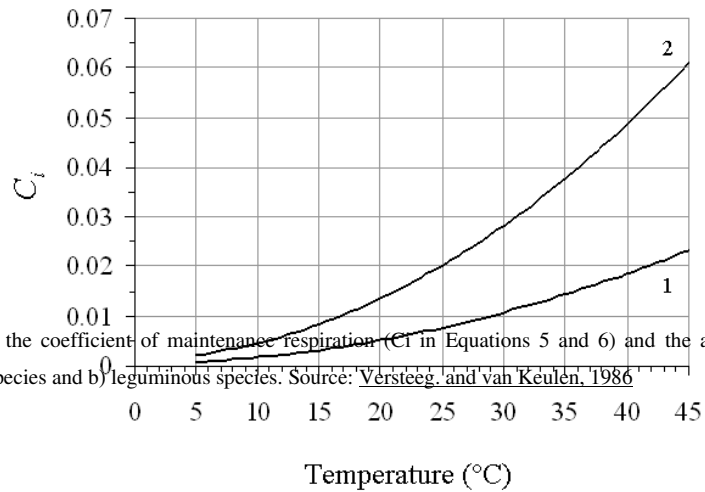


Figure 3. The relationship between the coefficient of maintenance respiration (C_1 in Equations 5 and 6) and the average growth period temperature for 1) non-leguminous species and 2) leguminous species. Source: Versteeg, and van Keulen, 1986

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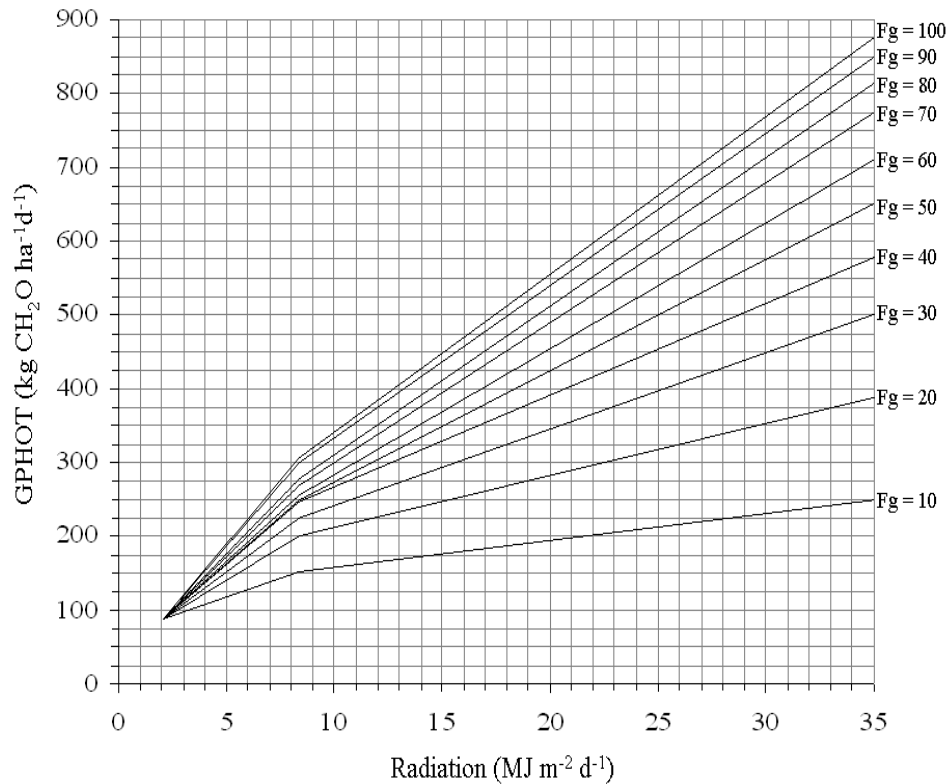


Figure 4. For the closed canopy (linear growth period), the daily gross photosynthesis rate (GPHOT, kg CH₂O ha⁻¹d⁻¹) is calculated from the maximum photosynthesis rate of the single leaf at light saturation (Fg, kg CO₂ ha⁻¹h⁻¹) and the daily radiation (MJ m²d⁻¹) in latitudes between 0-40. Source: [Versteeg and van Keulen, 1986](#)

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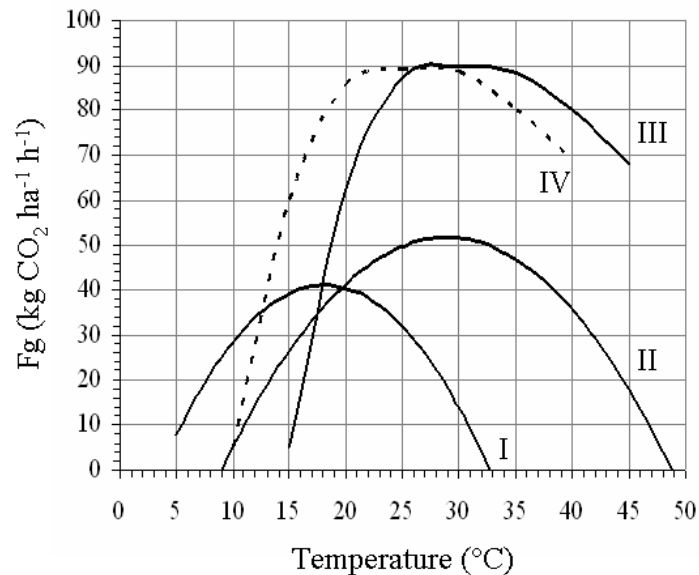


Figure 5. In four groups of crops, the amounts of photosynthesis (Fg, kilograms of CO₂ per hectare) at light saturation are related to temperatures: I) temperate C₃ species (wheat, barley, potatoes, sugar beet), II) warm climate C₃ species (rice, soybeans, cotton, cassava), III) legumes (corn, sorghum, millet, sugarcane) and IV) cultivars of C₄ species (corn, sorghum). Source: [Versteeg and van Keulen, 1986](#).

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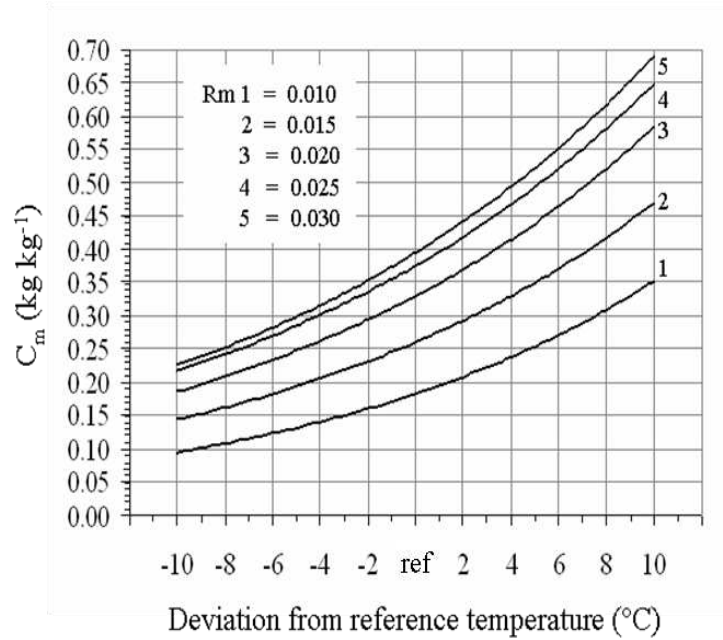


Figure 6. Correction of maintenance respiration coefficient (C_m , kg kg^{-1}) for deviation from reference temperature (ref) during the linear growth period (46 days) in 5 groups of crop species (Table 1) with different daily respiration rates (R_m , $\text{kg CH}_2\text{O kg DM}^{-1} \text{d}^{-1}$), reference temperature for C3 and c4 species is 20 and 30 °C, respectively. Source: [Versteeg, and van Keulen, 1986](#).

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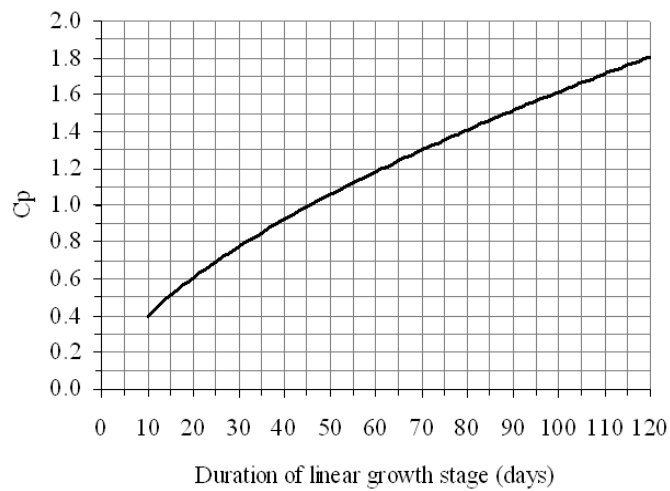


Figure 7. C_p factor for correction of maintenance respiration coefficient (C_m) at different durations of the linear growth period, C_p is equal to 1 for a linear growth period of 46 days. Source: [Versteeg, and van Keulen, 1986](#)

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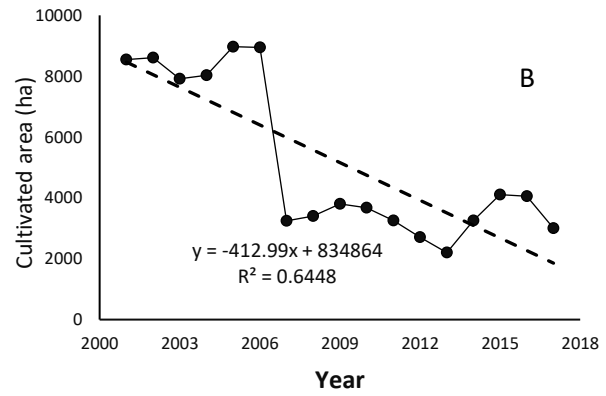
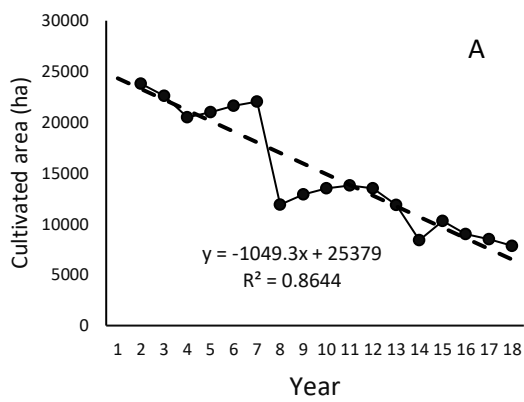


Figure 8. Trend of wheat (A) and sugar beet (B) cultivated area variations in the Torbat-e Heydariyeh

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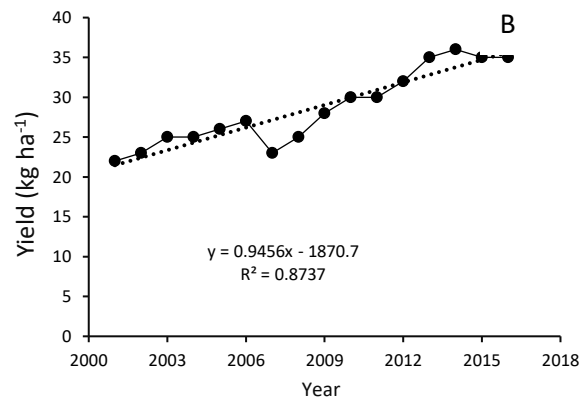
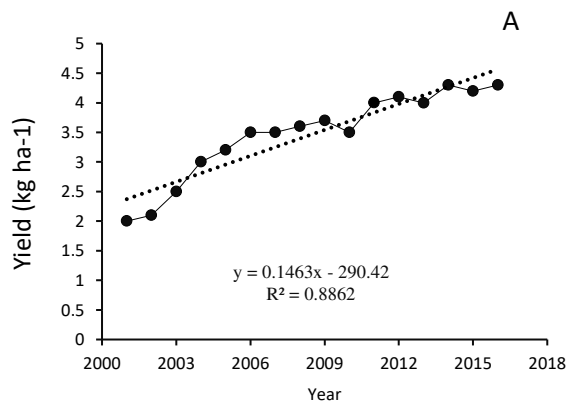


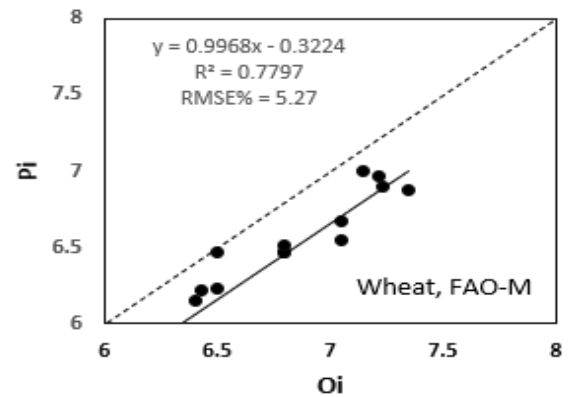
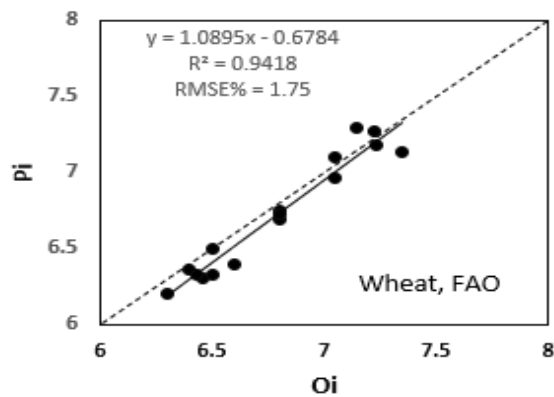
Figure 9. Trend of grain wheat (A) and root sugar beet (B) yield variations in the Torbat-e Heydariyeh

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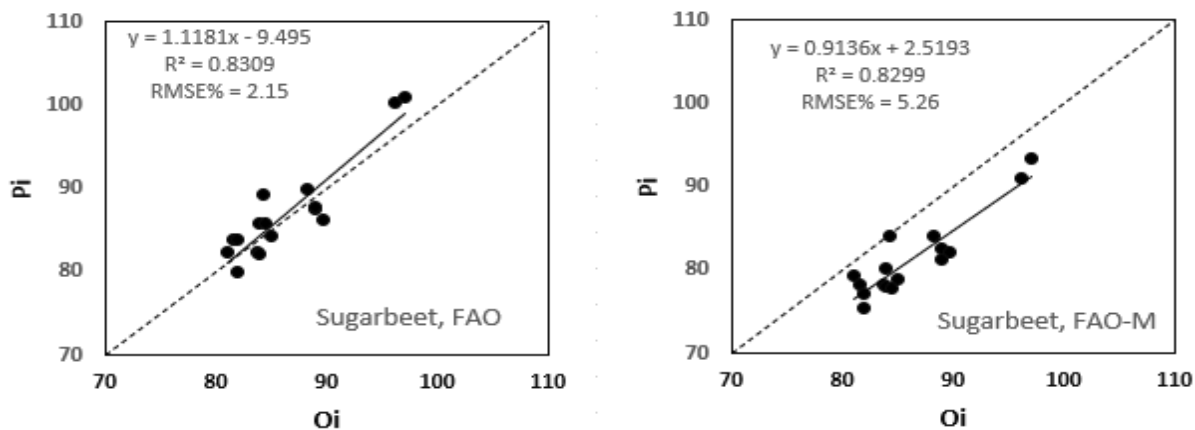


Figure 10. Comparisons for the regression line with 1:1 line and R2 for Potential yield of wheat and sugar beet obtained via the FAO and modified FAO (FAO-M) method

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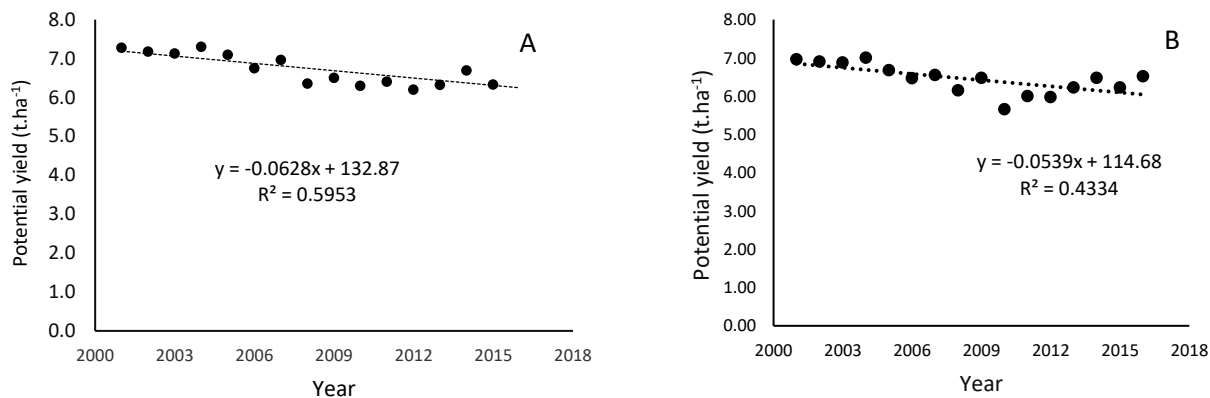


Figure 11. Potential yield of wheat obtained via the FAO (A) and modified FAO (B) method

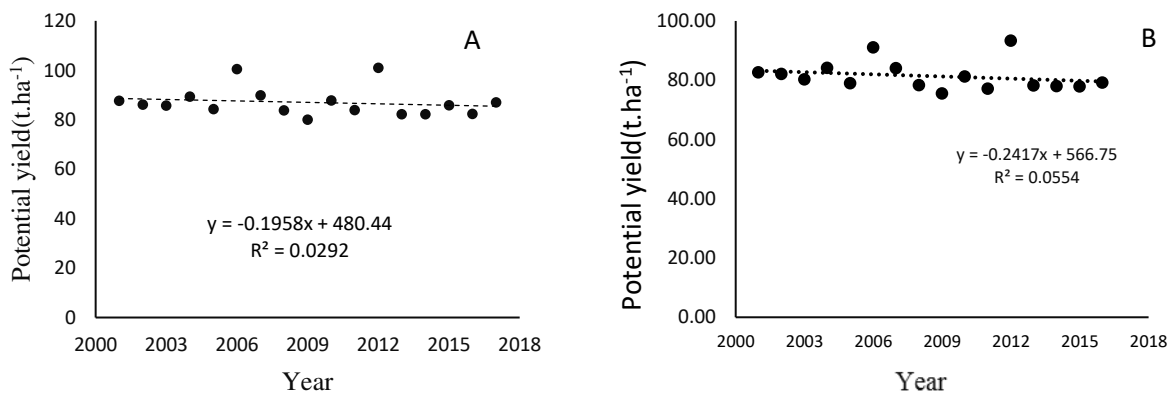


Figure 12. Potential yield of sugar beet obtained via the FAO (A) and modified FAO (B) method

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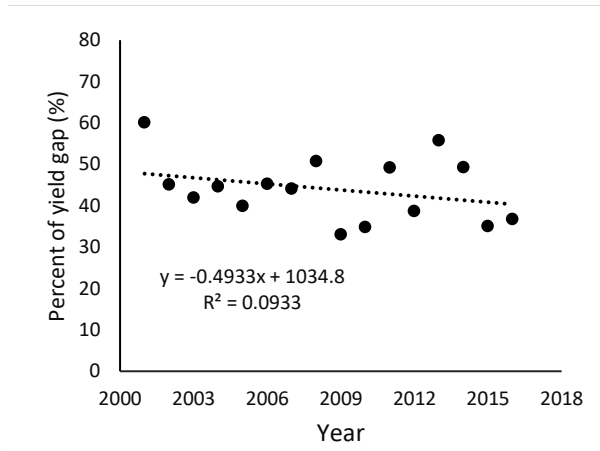
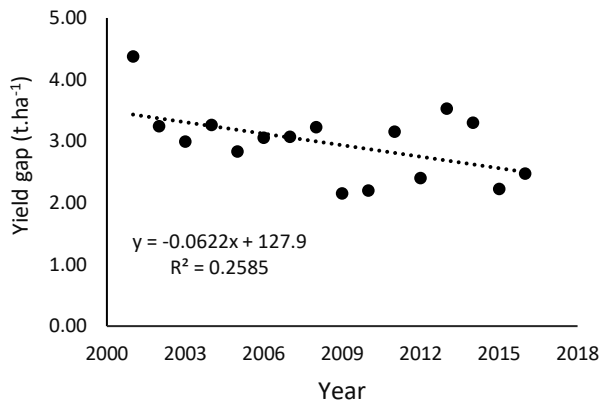


Figure 13. Trend of wheat yield gap and percentage of yield gap in the Torbat-e Heydariyeh region

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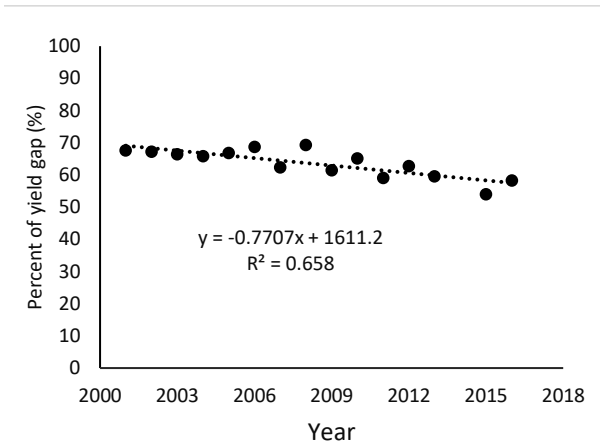
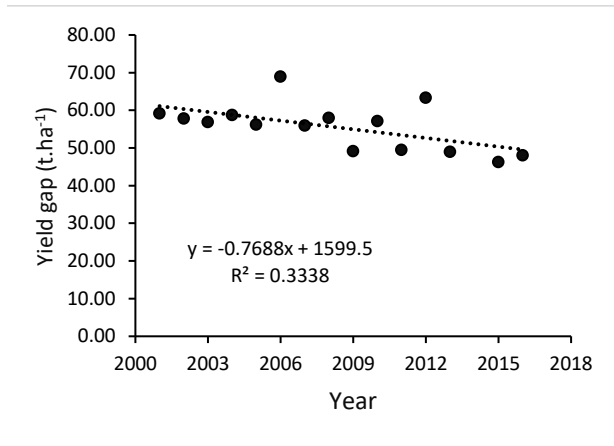


Figure 14. Trend of sugar beet yield gap and percentage of yield gap in the Torbat-e Heydariyeh region

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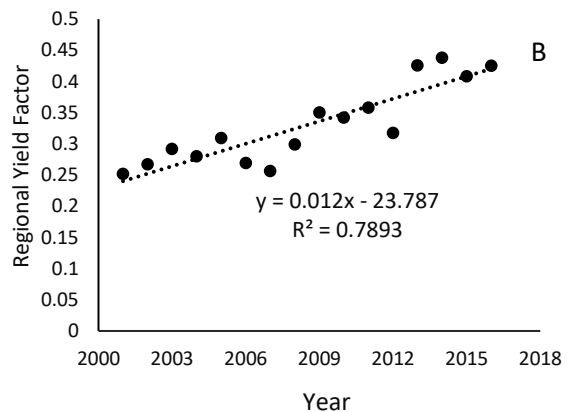
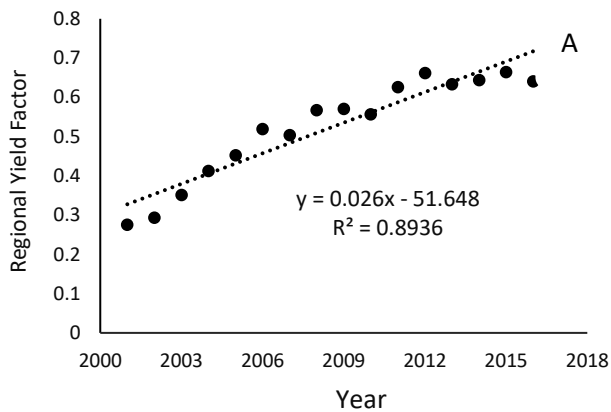


Figure 15. Trend of wheat (A) and sugar beet (B) regional yield factor in the Torbat-e Heydariyeh region

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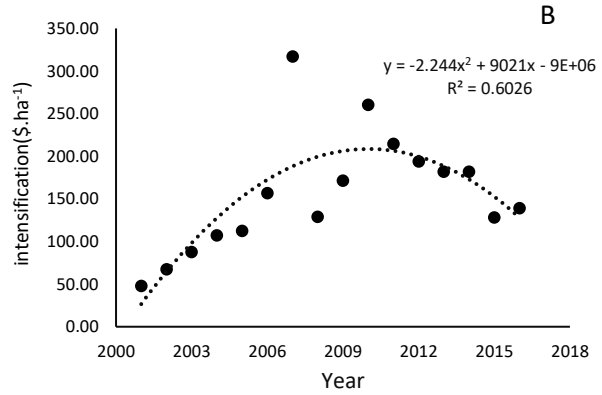
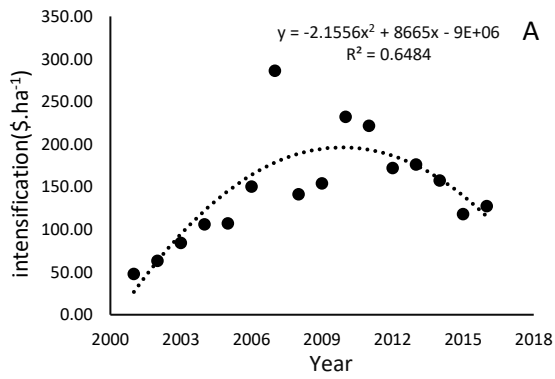


Figure 16. Trend of intensification of wheat (A) and sugar beet (B) systems in the Torbat-e Heydariyeh region

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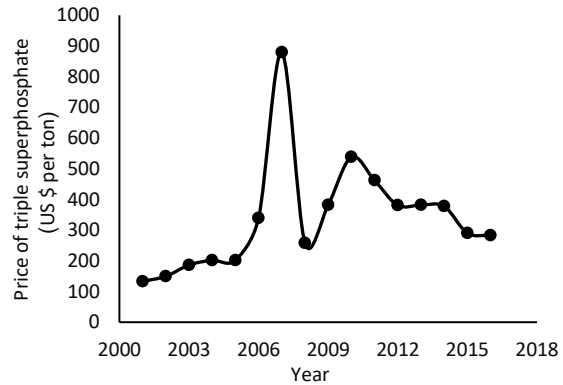
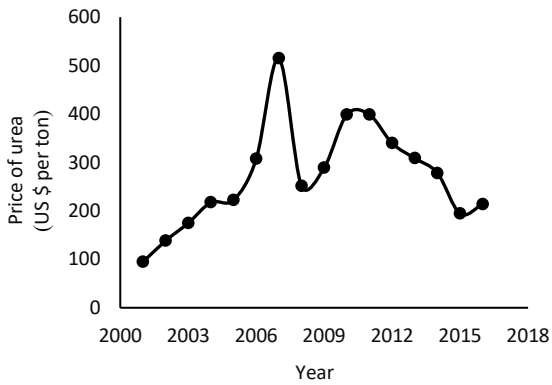


Figure 17. Trend of global changes in the price of urea fertilizer from 2001-to 2016

Figure 18. Trend of global changes in the price of triple superphosphate fertilizer from 2001-to 2016

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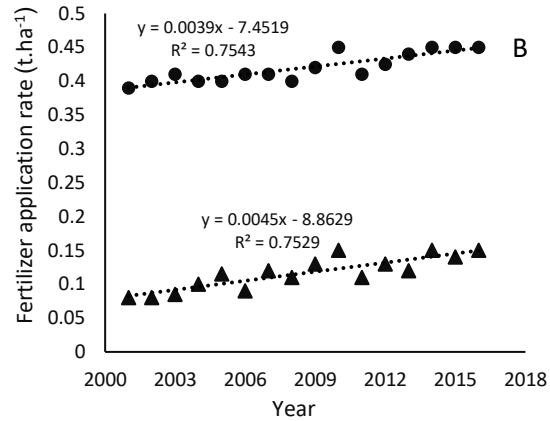
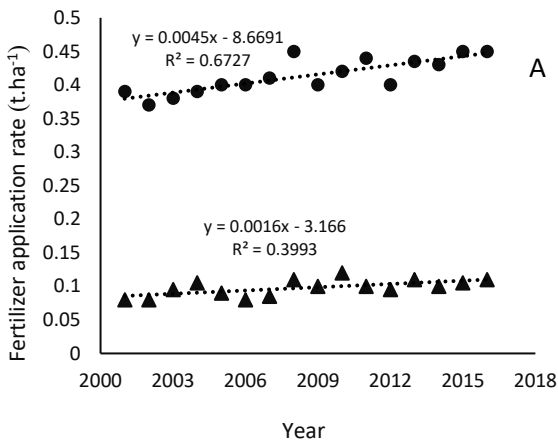


Figure 19. Trend of changes in urea and triple superphosphate fertilizer application in the wheat (A) and sugar beet (B) systems in the Torbat-e Heydariyeh region from 2001-to 2016

Superphosphate ▲ Urea ●

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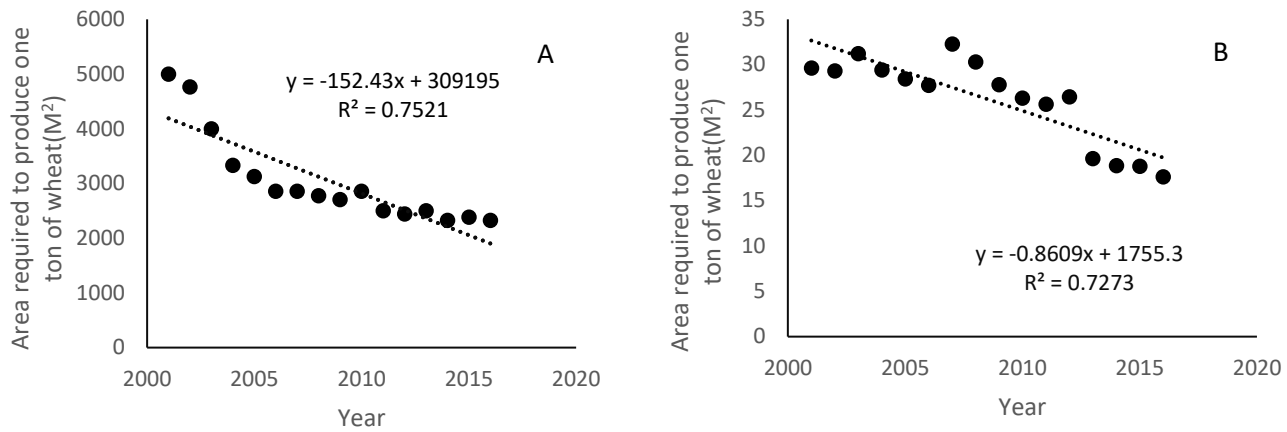


Figure 20. Trend of Area required to produce one ton of wheat(A) and sugar beet (B) systems in the Torbat-e Heydariyeh region from 2001-to 2016

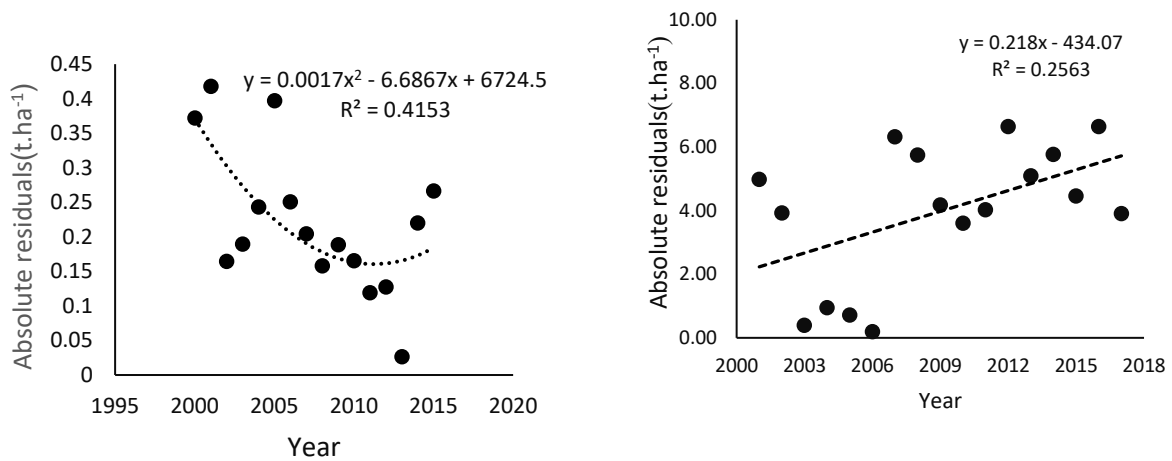
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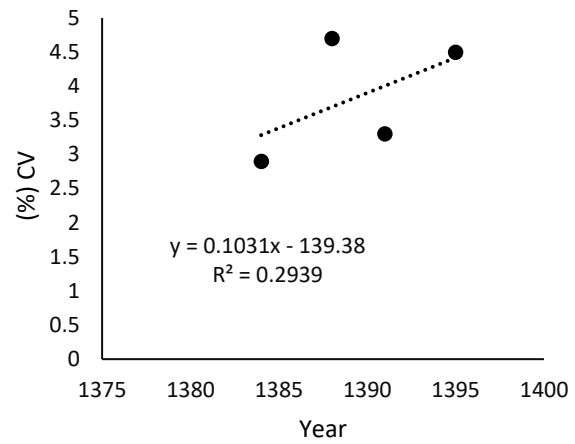
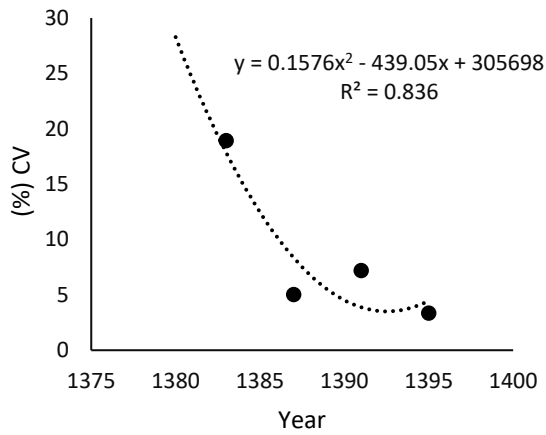
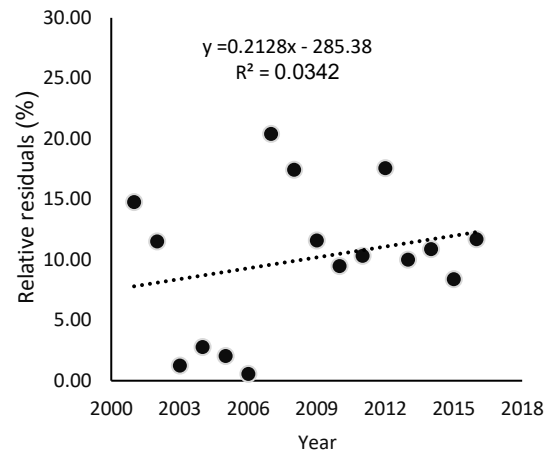
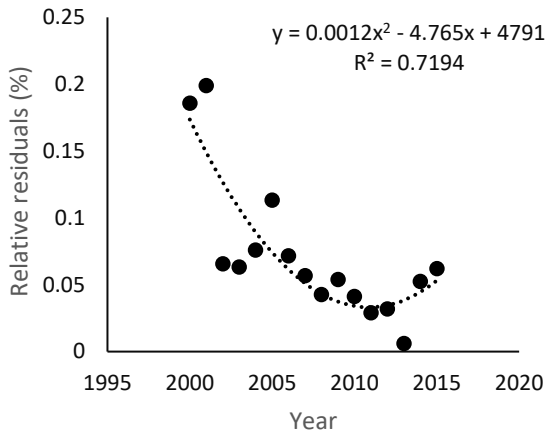
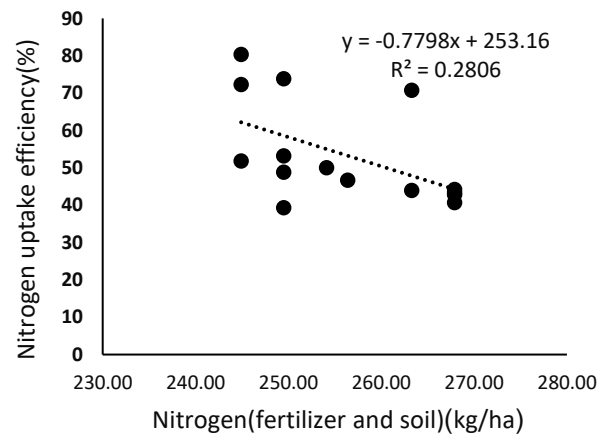
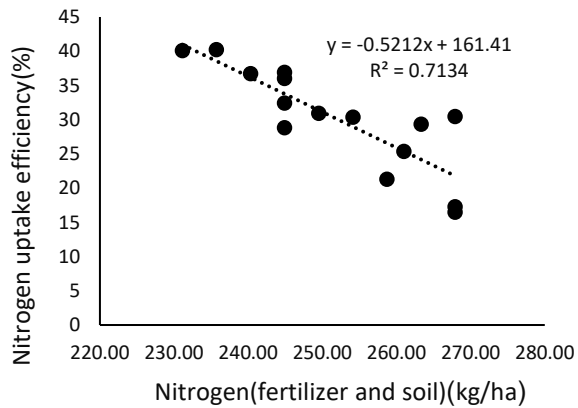


Figure 21. Trend of changes in absolute, relative residual values and coefficient of variation of wheat yield in the Torbat-e Heydariyeh region

Figure 22. Trend of changes in absolute, relative residual values and coefficient of variation of sugar beet yield in the Torbat-e Heydariyeh region

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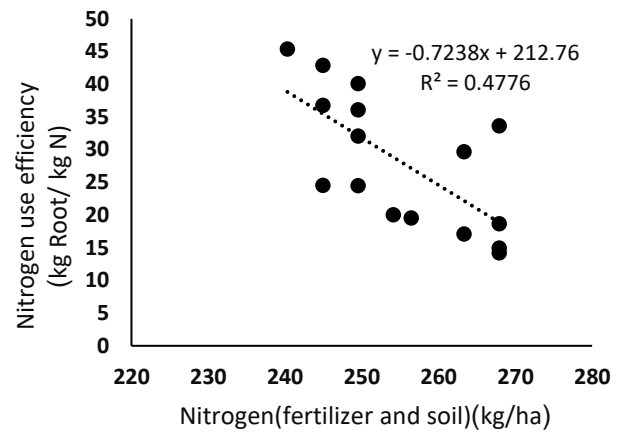
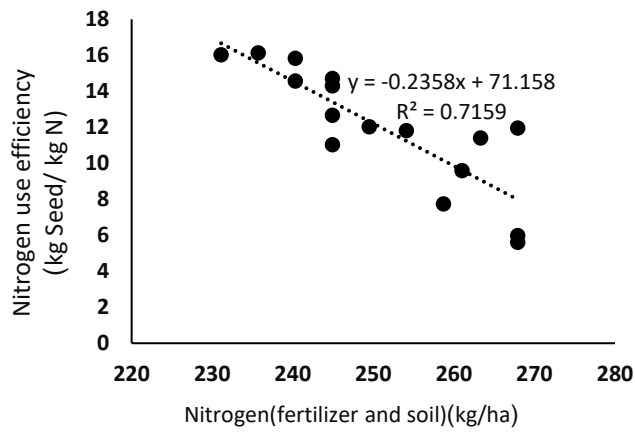
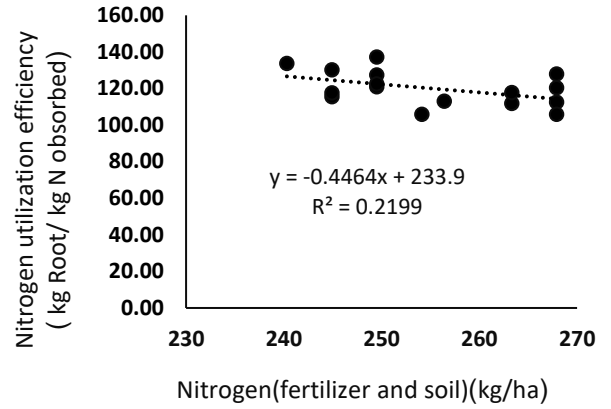
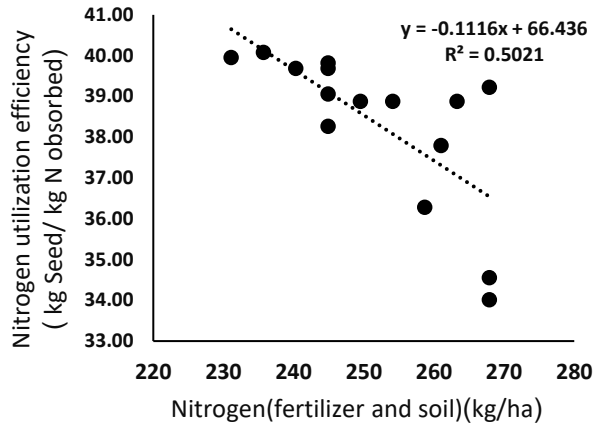


Figure 23. Trend of nitrogen uptake efficiency, nitrogen utilization efficiency, and nitrogen use efficiency of wheat in the Torbat-e Heydariyeh region

Figure 24. Trend of nitrogen uptake efficiency, nitrogen utilization efficiency, and nitrogen use efficiency of sugar beet in the Torbat-e Heydariyeh region