Turkish Journal of Agriculture and Forestry

Volume 46 | Number 6 Article 9

1-1-2022

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Recommended Citation

TÜRKSEVEN, SÜLEYMAN GÜRDAL; ULUDAĞ, AHMET; DEMİRCİ, MEHMET; and SERİM, AHMET TANSEL (2022) "Herbicide resistance in Avena sterilis subsp ludoviciana populations from the wheat fields of Turkey," *Turkish Journal of Agriculture and Forestry*: Vol. 46: No. 6, Article 9. https://doi.org/10.55730/1300-011X.3050

Available at: https://journals.tubitak.gov.tr/agriculture/vol46/iss6/9

Turkish Journal of Agriculture and Forestry

http://journals.tubitak.gov.tr/agriculture/

Research Article

Turk J Agric For
(2022) 46: 888-897
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doi:10.55730/1300-011X.3050

Herbicide resistance in *Avena sterilis* subsp *ludoviciana* populations from the wheat fields of Turkey

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Received: 15.01.2022 • **Accepted/Published Online:** 17.08.2022 • **Final Version:** 05.12.2022

Abstract: *Avena sterilis* L. subsp *ludoviciana* (Durieu) Gillet and Magne (AVELU) is among the most common and economically important grass weed species, especially in wheat fields of Turkey; therefore, the herbicides with the same mode of action (ACCase and ALS/AHAS inhibitors) are used to control have been successively applied without incessant by farmers. A study was conducted to find out the extent of wild oat problems throughout Turkey including herbicide resistance. This paper includes results of determining the herbicide resistance status of AVELU populations to ACCase and ALS inhibitors that are fenoxaprop (Fen), pinoxaden (Pin), tralkoxydim (Tra), mesosulfuron+iodosulfuron (MeI), and proxycarbazone+mesosulfuron (PrM). AVELU seeds were collected from 213 wheat fields throughout Turkey in 2014–2015 and the response to selected five herbicides was tested under screen-house. Dose-response tests showed that only 42 populations were controlled by all five herbicides. The number of populations that were not controlled varied by herbicides, which were 150, 48, 25, 100, and 100 populations for Fen, Pin, Tra, MeI, and PrM, respectively. Nine populations were resistant to all herbicides and 72 to four of herbicides out of 155 multiple resistance populations. The high number of multiple resistances and higher resistance indexes show the seriousness of the problem. Although resistance to MeI and Tra herbicides are still developing, Fen resistance seems completed and reached moderate and high resistance levels. Integrated weed management is an inevitable challenge to sustain wheat production, a staple crop for Turkey.

Key words: ACCase inhibitors, ALS inhibitors, multiple resistance, cross resistance, wheat

1. Introduction

Wheat is an important cereal worldwide because it has rich carbohydrate and protein content; therefore, it is produced in nearly all countries (Cançelik et al., 2021). It is used as a raw material for processed food and beverages, and its straw and husk are considered a valuable source for animal feed. Annual demand for wheat has been higher than the crop produced in Turkey, which has steadily declined during the last decade and redounded 17.65 million t of 6,6223,900 ha area harvested in 2021 (TUIK, 2022[1]). Therefore, the gap between wheat supply and demand carried Turkey to the first rank in the list of World Wheat Imports in 2019 by paying approximately US$ 2,3 billion (Workman, 2020).

Wheat husbandry has been spread along all regions of Turkey except the East Black Sea area (TUIK, 2022[1]). Wheat yield is limited by many factors such as cost of crop production, high temperatures, drought or water shortage, pests, diseases, and weeds (Elbasyoni, 2018; Oerke, 2006; Nezhadahmadi et al., 2013). Weeds are undesirable troublesome plants grown in the fields and cause a serious problem for the crop itself via reducing yield and quality and obstructing husbandry activities (Anderson, 1983; Juraimi et al., 2005). Although varying weed control methods and integrated strategies are applied to control weeds, chemical weed control is the most preferred method, which causes many problems (Uludag et al, 2006; Üstüner et al., 2020; Serim, 2022). Using the herbicide that belonged to the same mode of action continuously has resulted in herbicide resistant weeds in wheat as well as other corps (Walsh and Powles, 2014; Nakka et al., 2019).

The species belonging to *Avena* genus have been ranked among the most pernicious weeds in many grain and pulse crops in the world (Holm et al., 1991). The genus has many agriculturally important weeds such as *A. fatua* L. and *A. sterilis* L. that widely distributed in agricultural

[1] TUIK (2022). Agricultural statistic in Turkey [online] https://biruni.tuik.gov.tr/medas/?kn=92&locale=tr [Accessed 17 April 2022]

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and nonagricultural areas in Turkey (Taştan and Erciş, 1991; Uludağ et al., 1999; Uludağ, 2003). *A. sterilis* L. has two subspecies: *A. sterilis* subsp *sterilis* L. and *A. sterilis* subsp *ludoviciana* (Durieu) Gillet et Magne (from now on AVELU) (Dogan, 1985). Yield loss caused by *Avena* species reaches 72% in spring barley and 50% in wheat (Beckie et al., 2012; Mahajan and Chauhan, 2021). Furthermore, *Avena* spp. may reduce protein content in the wheat seeds and native biodiversity, use more nitrogen from the soil and create a strong seed bank (Wimschneider et al., 1990; Satorre and Snaydon, 1992; Maxwell et al., 2007). Moreover, the members of *Avena* spp. have also crucial importance in herbicide-resistant weed species in small grains, especially in wheat because of their ability to gain resistance to the herbicides applied continuously for a long while.

Herbicide resistance is a phenomenon that has occurred in the fields where the herbicide used intensively and continuously when herbicide rotation and implementation of other methods were ignored. Herbicide resistance has led to further environmental and agronomic problems such as applying the herbicides at overdoses or repeating them several times even if these practices have not been recommended. Herbicide resistant weed populations in wheat fields have commonly been found worldwide and have been recorded in 341 cases from many countries (Heap, 2022[2]). In Turkey, it was reported *A. fatua*, *A. sterilis* subsp *sterilis*, *Sinapis arvensis, Alopecurus myosuroides, Phalaris brachystachys* spp. resistant to ACCase inhibitors (A/1), ALS inhibitors (B/2), Synthetic Auxins (O/4) (Sizer and Tepe, 2016; Uludağ et al., 2003a; Uludağ et al. 2003b; Torun and Uygur, 2018; Türkseven and Nemli, 2015). Recognizing the first herbicide- resistant population in *Avena* populations date back to 1985 in Australia and 1997 in Turkey, which were verified later (Heap, 2022[2]). Then, the resistance cases belonging *Avena* spp. increased, and not only limited to ACCase and ALS inhibitor herbicides but also expanded with including multiple or/and cross resistance for the herbicides belonging other mode of actions and reached 75 cases worldwide (Heap, 2022[2]).

ACCase inhibitors and ALS inhibitors have been registered and widely used to control *Avena* spp in cereal fields of Turkey since the 2000s, respectively (Uludag ve Demir, 1996; Uludag, 2003). The first ACCase resistant *A. sterilis* and *A. fatua* populations were reported by Uludağ et al. (2003a) and Turkseven and Nemli (2015), respectively. Uludağ et al. (2007) indicated that some *A. sterilis* populations resistant to Fen showed cross-resistance to clodinafop, diclofop, fluazifop, Tra, tepraloxydim, clethodim, cycloxydim, or sethoxydim at various degrees in the East Mediterranean Region of Turkey, a population resistant to CHD and APP had multiple resistant to flamprop but no resistance detected to trifluralin, imazamethabenz or MeI. Turkseven and Nemli (2015) found that some *A. fatua* populations had resistance to diclofop, Fen, clodinafop, and Tra, and cross-resistance was also found between the resistant populations in the Marmara Region of Turkey. Clodinafop, MeI and pyroxulam resistant *A. fatua* populations were also determined in Osmaniye province wheat fields by Torun and Uygur (2018). The authors also indicated that the populations had the cross and multiple resistance at various degrees to both groups. In the Diyarbakır province *A. sterilis* populations were found resistant to clodinafop but not to MeI (Sizer and Tepe, 2016). There is no comprehensive weed survey, despite these regional studies, on AVELU resistance to the herbicides in Turkey. A nationwide study was conducted to find out the current situation of herbicide resistant *Avena* spp. in wheat fields and characterize resistant populations. This paper focuses on AVELU populations resistant to ACCase and ALS inhibitor herbicides, and their cross and multiple resistance populations as well as resistance levels.

2. Material and methods

2.1. Seed sampling and general procedures

AVELU seeds were collected from 213 wheat fields from all geographical regions of Turkey according to amount of wheat cultivation area in 2014 and 2015: 45 samples from the Mediterranean (the Adana, Kahramanmaraş, Mersin, Osmaniye, and Hatay provinces), 58 samples from the Southeast Anatolia (the Diyarbakır, Mardin, Şanlıurfa, Batman, Gaziantep, and Siirt provinces), 6 samples from the East Anatolia (the Van, Erzurum, and Iğdır provinces), 54 samples from the Central Anatolia (the Ankara, Konya, and Karaman provinces), 15 samples from the Aegean (the Aydın, Denizli, İzmir, Manisa, Muğa, and Uşak provinces), 24 samples from the Marmara (the Balıkesir, Bursa, Çanakkale, Edirne, and Tekirdağ provinces), 11 samples from the Black Sea (the Bolu, Düzce, Amasya, Çorum, Samsun, and Tokat provinces) regions.

Threshed seeds were dried under shadow for 3 days, then stored in paper bags under dry room conditions until screen tests and whole plant dose-response bioassays were performed. All tests were carried out in Ege University Campus in İzmir, Turkey. Seeds were kept +4 °C to break seed dormancy for a month followed by sodium hypochlorite treatment for 30 s, then rinsing 60 s with distilled water twice for sterilization. Seeds were placed in petri dishes with two layers of filter papers (Whatman No:1) in a growth chamber and 7 mL of distilled water was added. Germinated seeds were transferred to pots after 3–4 days to obtain seedlings.

Herbicides were applied by using a knapsack sprayer mounted flat fan nozzles (Lechler 11002) at 200 kPa with

[2] Heap I (2022). The International Herbicide-Resistant Weed Database [online] www.weedscience.org [Accessed 12 January 2022]

196 l ha^{-1} water volume when the seedling was at two-three-leaf stage.

2.2. Screen test

The experiment was conducted in a screen-house during the spring and autumn seasons in 2014. Germinated seeds were transferred to pots (7.6 × 7.6 × 10 mm) that had been filled with a 1:1 mixture of soil: peat and placed in a screen-house. Seedlings were thinned to one plant in each pot and watered with tap water when needed. Each replication consisted of one pot.

Twice the recommended rates of Fen, Pin, Tra, MeI, or PrM (Table 1) were applied. The efficacy of herbicides was visually evaluated 21 Days After Treatment (DAT). An individual killed totally or affected over 80% by herbicide was considered sensitive, and all remainings resistant.

2.3. Whole plant dose-response bioassay

Suspected herbicide-resistant populations according to the screen test mentioned above underwent whole plant dose-response bioassay in a screen house to characterize the resistance levels of AVELU accessions. The seedlings were transferred to 10 cm diameter pots when they reached to two–three cm length then thinned to one plant in each pot. Logarithmic doses of herbicides, 0.5X, X, 2X, 4X, and 8X (X: recommended rates of given herbicide), were applied during the spring and autumn seasons in 2015. The plants were cut from the soil surface at 21 DAT, dried at 65 °C, and weighed.

2.4. Statistical analysis

All experiments were set in a completely randomized block design with four replications (one pot per replicate). The dry weight data obtained from dose-response experiment were subjected to nonlinear regression analysis. Three-parameter log-logistic regression model was employed to determine Gr_{50} (the herbicide rate, causing 50% dry matter reduction) values of the populations (Seefeldt et al., 1995; Streibig, 1988). Lower limit (C term) was fixed at zero (Knezevic et al. 2007; Ulloa et al. 2011). The log-logistic regression was presented in Formula 1.

$$Y = \frac{D}{1 + \exp\left(b(\log(x) - \log(Gr50))\right)} \quad (1)$$

where y represents seedling dry matter at herbicide treated rate x; D, b, and GR_{50} represent upper limit, slope, and herbicide rate that reduced seedling dry matter by 50%, respectively.

The log-logistic equation was modelled utilizing the DRC (analysis of dose-response curves) statistical add-on package in the R statistical software (R Core Team, 2020). The resistance level of herbicides was determined using the Relative Index (RI) which calculated the GR_{50} values of the resistant population divided by the GR_{50} values of the sensitive population, 14ANK05. The sensitive population was effectively controlled by lower rates of all herbicides verified with a pre-trial test. The RI is presented in Formula 2.

$$RI = \frac{GR50\ (resistant\ biotype)}{GR50\ (sensitive\ biotype)} \quad (2)$$

In addition, Resistance Levels (RL) of populations were classified similar to the study conducted by Ahmad-Hamdani et al. (2012) which were based on GR_{50} values for the resistant populations and have been described as highly resistant (>10), moderately resistant (>5 to 10), low resistant (>2 to 5), and sensitive (<2).

3. Results

3.1. Status of AVELU populations for herbicide resistance

Status of populations was determined through screen tests. Out of 213 AVELU populations, 42 were sensitive to all five herbicides whereas 154, 51, 25, 106, and 111 populations were not effectively controlled by Fen, Pin, Tra, MeI, or PrM, respectively (Figure 1). There are provinces that no Fen or ALS resistant populations in spite of high number of populations were detected for these herbicides. The screen test revealed that 42 populations were resistant only one herbicide, mainly Fen resistance

Table 1. Some features of the herbicides used in the experiments.

Herbicide names	Abbreviations	Recommended rates (g ai ha^{-1})	Safeners (g ai ha^{-1})	Commercial products
Fenoxaprop-p-ethyl	Fen	60	Mefenpyr-diethyl (41.4)	Puma Super 75 (Bayer)
Pinoxaden	Pin	40.5	Cloquintocet-mexyl (18)	Axial 050 EC (Syngenta)
Tralkoxydim	Tra	300	-	Splendor (Syngenta)
Mesosulfuron methyl +iodosulfuron methyl sodium	MeI	9+1.8	Mefenpyr-diethyl (27)	Atlantis WG (Bayer)
Propoxycarbazone sodium + Mesosulfuron methyl	PrM	13.5+9	Mefenpyr-diethyl (27)	Attribut Super WG 20 (Bayer)

while most herbicide-resistant populations have multiple resistance to ACCase and ALS inhibiting herbicides. Three populations from three differt regions namely the Mediterranean, Southeast Anatolia, and Central Anatolia regions were not controlled by any of the five herbicides. Seventy-two were resistant to four herbicides (2 ALS and 2 ACCase) out of 155 populations have multiple resistance. Cross-resistance was seen at two ACCase resistant and three ALS-resistant populations.

The distribution of suspected herbicide-resistant AVELU populations in the Mediterranean, Southeast Anatolia and Central Anatolia regions were very similar to each other, and Fen-resistant AVELU populations were the highest whereas Tra populations were the lowest (Figure 2). There were apparent differences among the regions in terms of the number of suspected herbicide-resistant populations, even if the sample sizes were not the same. The reason for the differences between the sample sizes of the regions was related to the amount of area allocated to wheat cultivation in each region. Some regions such as East Anatolia and Black Sea had limited wheat fields compared to other regions (TUİK, 2022[3]).

3.2. Level of resistance in populations

Populations that were not controlled by a given herbicide after the screen test were labelled as suspected resistant and underwent to further investigation to reveal the level of resistance for that herbicide. The seeds belonged to 11 suspected resistant populations lost their viability or infected by pathogens, so they could not include to dose-response bioassays. Showing of all data, GR_{50}, B, D, and RI, may not be explicative because there are high number of herbicide-resistant AVELU populations for each herbicide; therefore, the data belonged to five herbicide-resistant populations which were at various resistance levels and one herbicide sensitive are shown in Tables 2–6. The GR_{50} values of Tra resistant 25 populations varied 511.17–2555.85 g ai ha^{-1} and the lowest and highest RI were 2.9–14.4, respectively, compared to the sensitive check (Table 2). The GR50 values of 48 Pin resistant populations varied 45.03–126.8 g ai ha^{-1} with 1.5–4.8 RI values (Table 3). The GR50 values of 150 Fen-resistant populations ranged 47.01 and 93.8 g ai ha^{-1}, and their RI values varied 7.3–14.7 (Table 4). GR50 of 100 of PrM varied 37.7–144.1 g ai ha^{-1} for resistant populations, and RI values were 3.5–13.2 (Table 5). In terms of the second ALS inhibitor herbicide MeI, GR_{50} values calculated from 100 resistant populations were 9.5 to 20.1 g ai ha^{-1}, and RI values of them varied 1.5–3.1 (Table 6).

The median resistance index was 10.21, 6.57, 3.18, and 2.32, 6.88 Fen, Pin, Tra, MeI, or PrM, respectively (Figure 3). The resistance index of MeI populations was very similar but highly different for Tra ones. Characterization tests revealed that 13 populations were sensitive, which were resistant according to prescreening tests (Table 7). Response of populations to Pin or MeI was low-level resistance mostly, Tra or PrM was mostly moderately resistant. High resistance was the most common to Fen.

4. Discussion

According to screening test, only 42 out of 213 AVELU populations were sensitive to all five herbicides tested in this study. Among the resistance cases, suspected Fen resistance was the most common one where 72% of the population had, followed by 52% and 50% by suspected MeI and suspected PrM, respectively, two ALS inhibitor herbicides. Suspected resistance to other two ACCase inhibitors was less common, 24% for Pin and 12% for Tra. The first globally reported cases on AVELU resistance to herbicides were in Australia in 2002 and 2005 that were to flamprop-methyl and iodosulfuron-methyl-Na, respectively in wheat fields (Heap, 2022[4]). In Turkey, the first cases related to *A. sterilis* including both subspecies without separating were reported in 2001 as ACCase resistant, mainly Fen and clodinafop cases (Uludağ et al., 2001a, b; Uludağ et al., 2003a; Uludağ et al., 2007). It was the first herbicide resistance case in Turkey, although APP-resistant *Alopecurus myosuroides* was reported in the same years (Uludağ, 2003; Uludağ et al, 2003b). Currently, there have been eight herbicide-resistant cases in AVELU mostly to ALS and ACCase inhibitors (Heap, 2022[#]). However, some cases of AVELU might be reported under *A. sterilis* cases without discriminating subspecies as was mentioned in some literature (Uludağ, 2003).

The highest number of resistant populations was found in the Mediterranean, Central Anatolia, and Southeast Anatolia regions with the highest wheat sown areas; however, it should be kept in mind that the number of samples was not the same for all regions because the regions aforementioned had prominent in terms of wheat production fields. Furthermore, it is common practice in Turkey, ALS, and ACCase herbicides have been applied not only in wheat but also rotational crops or second crops preceding or following wheat, which might have triggered herbicide resistance to both action mechanisms.

ACCase inhibiting herbicides, Fen, Tra, and Pin were respectively registered to control *Avena* spp. in 1989, 1991, and 2007, and ALS inhibitor herbicides, MeI and PrM introduced to the market in 2001 and 2007, respectively in Turkey (RPPP, 2009). Fen was the most popular selective grass herbicide in Turkey, and a total of 222,920 L commercial products was sold between 2001 and 2013

[3] TUIK (2022). Agricultural statistic in Turkey [online] ttps://biruni.tuik.gov.tr/medas/?kn=92&locale=tr [Accessed 17 April 2022]

[4] Heap I (2022). The International Herbicide-Resistant Weed Database [online] www.weedscience.org [Accessed 12 January 2022]

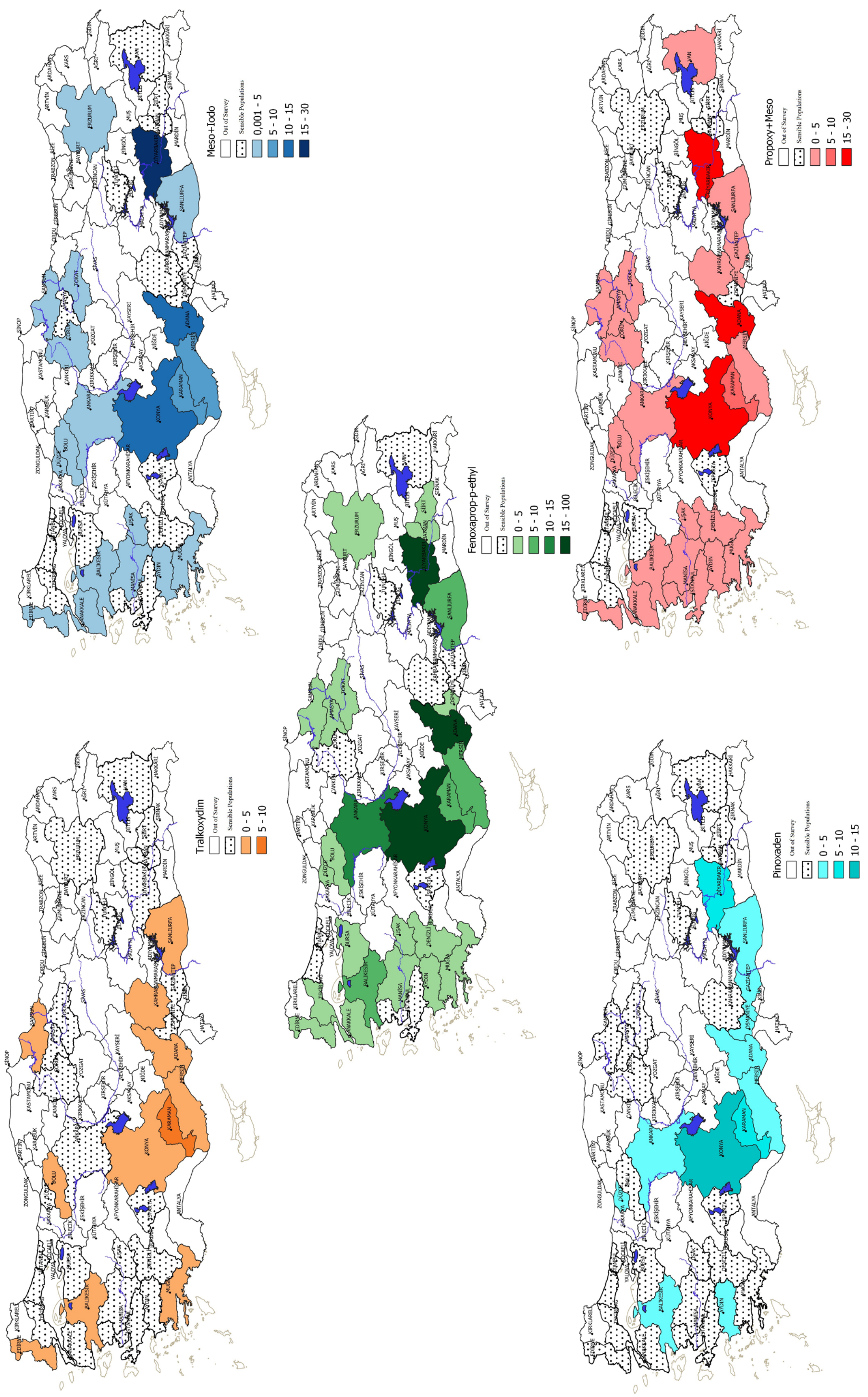

Figure 1. Distribution of the herbicide resistant AVELU populations for each herbicide (colour codes represent the number of resistant populations scaled for each herbicide differently; clear provinces means no seed sample obtained; and provinces with dotes none of AVELU populations resistant to given herbicide).

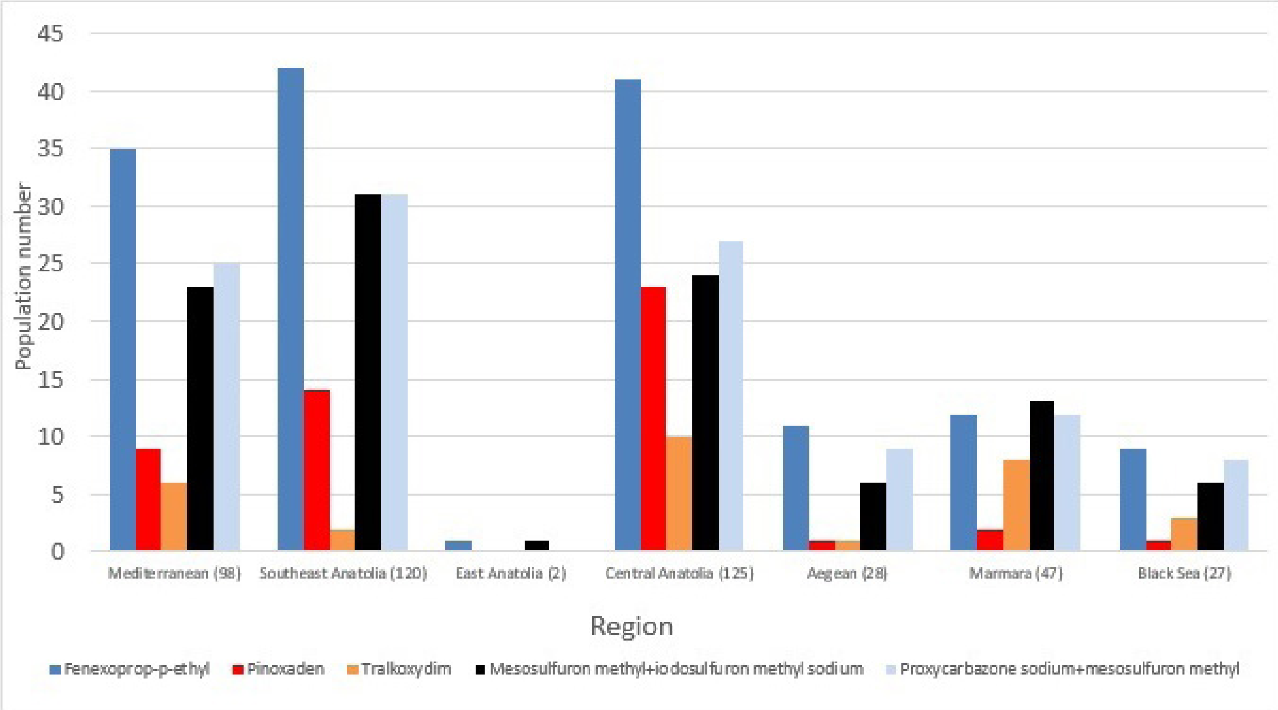

Figure 2. Distribution of the herbicide resistant populations among the regions. The number of populations tested is showed in the parenthesis.

Table 2. Parameters of the log-logistic analysis of Tra and resistance index (RI) for selected AVELU populations out of 25. Standard deviations are in parentheses (±).

Populations	B	D	GR_{50} (g ha^{-1})	RI
14ANK05	2.276 (0.864)	0.094 (0.003)	177.01 (41.56)	1
14ÇAN09	1.56 (0.856)	0.069 (0.005)	511.17 (116.96)	2.88
14DEN05	1.324 (0.391)	0.062 (0.006)	641.98 (178.24)	3.63
14KAR03	0.957 (0.287)	0.078 (0.007)	1294.3 (465.32)	7.3
13ADA05	0.971 (0.39)	0.072 (0.009)	888.44 (371.31)	5.01
14DEN02	1.568 (0.856)	0.069 (0.005)	2555.85 (584.82)	14.44

(DPPP, 2021). Tra was sold 25,300 L commercial products in the same period in the wheat fields of Turkey, which was not much popular one. Pin was firstly sold in 2011 and during the following 2 years, 28,272 L commercial products were sold. Total sales amount of MeI and PrM reached 21,326 kg and 8944 kg until 2013 (DPPP, 2021[5]). The sale of MEI was higher than PrM because it may control breadleaf weed in addition to grass weed species. The number of Pin resistant populations was relatively low because it was registered later than others for wheat fields. The AVELU seeds were collected from wheat fields probably after 3–4 years following the use of Pin. On the other hand, an *A. fatua* population that had not been exposed to Pin was found resistant to pinoxaden (Uludağ et al., 2008). In general, the difference in the number of resistant populations for each individual herbicide can be attributed to the long-term use of some herbicides compared to others or use frequency due to popularity among farmers (Owen and Powles, 2009; Travlos et al., 2011; Ahmad-Hamdani et al., 2012; Turkseven and Nemli, 2015).

The patterns of the herbicide resistance of the populations differed, the number of multiple resistant populations was higher than the populations that had

[5] DPPP (2021). Database of Plant Protection Products [online] http://www.tarim.gov.tr/GKGM/Belgeler/Bitki%20Sa%C4%9Fl%C4%B1%C4%9F%C4%B1%20Hizmetleri/2001-2012_Yillari_BKU_Istatistiki_Bilgileri.xls [Accessed 12 January 2022]

Table 3. Parameters of the log-logistic analysis of Pin and resistance index (RI) for selected AVELU populations out of 48. Standard deviations are in parentheses (±).

Populations	B	D	ED_{50}	R/S
14ANK05	0.927 (0.231)	0.101 (0.002)	29.3 (1.6)	1
15KAH01	1.016 (0.136)	0.087 (0.004)	45.03 (6.27)	1.54
15KON19	1.182 (0.193)	0.090 (0.004)	46.3 (6.58)	1.58
15DİY08	1.337 (0.165)	0.087 (0.004)	66.57 (7.53)	2.27
13BAL13	1.531 (0.207)	0.072 (0.003)	90.77 (9.40)	3.1
14DÜZ01	1.514 (0.183)	0.083 (0.003)	126.75 (12.58)	4.78

Table 4. Parameters of the log-logistic analysis of Fen and resistance index (RI) for selected AVELU populations out of 150. Standard deviations are in parentheses (±).

Populations	B	D	ED_{50}	R/S
14ANK05	1.522 (0.856)	0.111 (0.003)	6.40 (5.07)	1
14EDİ02	1.264 (0.286)	0.085 (0.085)	47.01 (9.18)	7.34
13ADA06	1.803 (0.329)	0.088 (0.004)	53.18 (5.49)	8.3
14AMA02	2.071 (0.424)	0.094 (0.005)	50.59 (4.80)	9.4
14TOK01	2.070 (0.514)	0.081 (0.004)	75.65 (8.91)	11.7
14KON151	1.501 (0.283)	0.068 (0.004)	93.81 (14.75)	14.66

Table 5. Parameters of the log-logistic analysis of PrM and resistance index (RI) for selected AVELU populations out of 100. Standard deviations are in parentheses (±).

Populations	B	D	ED_{50}	R/S
14ANK05	0.905 (0.293)	0.107 (0.003)	10.94 (0.77)	1
14AYD03	1.082 (0.209)	0.057 (0.004)	37.74 (7.85)	3.45
14EDİ04	1.243 (0.191)	0.084 (0.004)	52.41 (7.63)	4.8
14AYD11	1.614 (0.173)	0.079 (0.002)	76.44 (5.61)	6.99
14AMA05	1.251 (0.372)	0.063 (0.005)	87.35 (19.40)	7.89
14DİY24	2.588 (0.920)	0.048 (0.004)	144.08 (30.03)	13.16

Table 6. Parameters of the log-logistic analysis of MeI and resistance index (RI) for selected AVELU populations out of 100. Standard deviations are in parentheses (±).

Populations	B	D	ED_{50}	R/S
14ANK05	0.922 (0.301)	0.105 (0.002)	6.40 (0.61)	1
14KON09	1.330 (0.304)	0.085 (0.006)	9.53 (1.65)	1.48
14DEN01	2.818 (0.565)	0.082 (0.003)	15.21 (0.99)	2.38
14DİY23	1.857 (0.448)	0.068 (0.004)	16.18 (1.97)	2.53
14KON03	1.371 (0.377)	0.065 (0.005)	16.61 (3.46)	2.59
14EDİ07	1.519 (0.496)	0.048 (0.005)	20.13 (4.98)	3.14

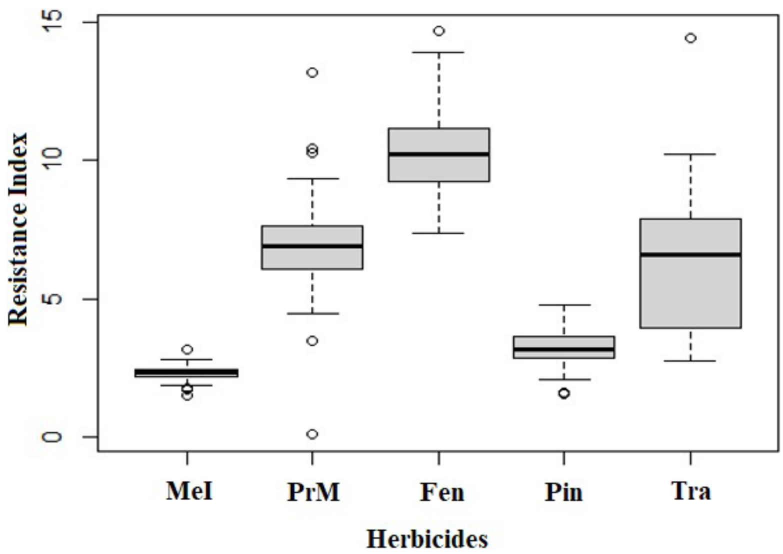

Figure 3. Resistance Index of populations for the herbicides used (Fen: Fenoxaprop, Pin: Pinoxaden, Tra: Tralkoxydim, MeI: Mesosulfuron+Iodosulfuron, and PrM: Proxycarbazone+Mesosulfuron).

Table 7. Classes of the populations according to their resistance levels. Maximum and minimum RL values are presented in the brackets (±).

Herbicides*	Sensitive	Low resistant	Moderately resistant	High resistant
Fen	-	-	66 (7.34–9.91)	84 (10.05–14.66)
Pin	2 (1.54–1.58)	46 (2.08–4.78)	–	–
Tra	–	7 (2.88–3.94)	16 (5.02–9.79)	2 (10.23–14.44)
MeI	10 (1.48–1.97)	90 (2.00-3.14)	–	–
PrM	1 (0.08)	6 (3.45–4.79)	90 (5.18–9.36)	3 (10.27–13.16)

*Fen: Fenoxaprop, Pin: Pinoxaden, Tra: Tralkoxydim, MeI: Mesosulfuron+Iodosulfuron, and PrM: Proxycarbazone+Mesosulfuron

resistance to only one herbicide formulation or had only cross resistance. Although 33 populations had only resistance to Fen, no population had only resistance to Pin or Tra. However, only five MeI and four PrM resistant populations were detected. MeI resistance at AVELU was reported from Iran (Gherekhloo et al., 2016). It was revealed that differential use frequency of herbicides in parallel to the registration date and the sold amount (RPPP, 2009; DPPP, 2021). Less cross-resistant only populations (only five with either ALS or ACCase) also support this conclusion by comparing the very high amount of multiple resistance (155). In Iran, there was cross resistance among some ALEVU populations to ACCase inhibitors from three different chemical groups, aryloxyphenoxypropionates (APPs, fops), cyclohexanediones (CHDs, dims), and phenylpyrazolin (PPZ, dens) (Sasanfar et al., 2017; Aghajani et al., 2021). In addition, our results are in parallel with earlier studies (Uludağ et al., 2007; Turkseven and Nemli, 2015; Sizer and Tepe, 2016; Torun and Uygur, 2018).

The high number of multiple resistance cases, which was 155 populations representing 73% of all studied populations in this study, can be due to the use of these herbicides under monoculture and rotational systems. Populations resistant to all five herbicides (9), four (72), and three (38) herbicides show the seriousness of the problem and the need for a challenge to chemical control. Indeed, there was only developing resistance to MeI that it had been already resistant to Fen in the early 2000s in the eastern Mediterranean area of Turkey, then in the mid-2010s MeI resistant and multiple resistant populations were found (Uludağ et al., 2007; Torun and Uygur, 2018). ACCase and ALS multiple resistant ALEVU populations were found in Iran (Heap, 2022#).

One of the measures of severity of resistance problem is resistance index (RI), which was very high for Fen with a median of 10.21 (7.34–14.66) showing all populations moderate or high resistance. The previous studies showed that the RI of Fen resistant *A. sterilis* populations ranged from 10 to >165 in Greece (Papapanagiotou et al., 2012), 3.5-fold to >25-fold in Australia (Ahmad-Hamdani et al., 2012), 10-fold to > 165-fold, 2.4-fold to > 8.0-fold in Turkey (Uludağ et al., 2007). It can be concluded Fen resistance is well established in Turkey, i.e. many populations have already completed their evolution. PrM and Tra also had higher RI values, but not as high as Fen. PrM resistance was mainly moderate, but the range was between no resistance to high resistance. A developing resistance was very apparent for MeI and Pin. These findings have shown that there was a great difference between the RI of the resistant populations due to different selection pressures, resistance mechanisms or cross-resistance in harmony with the previous studies (Powles and Yu, 2010; Uludağ et al., 2008). However, Papapanagiotou et al. (2012) found that the higher RI from *A. sterilis* Pin and Tra resistant populations with 10–18 and 14–266 compared to our results.

5. Conclusion

Wheat has been the main staple crop for Turkey, grown under monoculture, follow or rotational systems. Wild oat species have been among the most troublesome species since the 1980s depending on the region. The high number of multiple resistance and herbicides a population becomes resistant to and high resistant indexes clearly show how severe is the problem and points out the necessity for integrated weed management. Recent developments in the EU and Turkey such as the green deal also require new methods to be employed in weed management. Resistance populations of AVELU from Turkey have not been studied genetically, which can help to understand resistance mechanisms and find out more appropriate control techniques. In addition, epigenetics of AVELU resistance need to be revealed.

Acknowledgement

This study was supported by the Turkish Council for Scientific Research (TÜBİTAK), project code is 113O419.

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