Chapter

Improving Dual-Purpose Winter Wheat in the Southern Great Plains of the United States

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Abstract

This chapter covers the production and breeding status of winter wheat (*Triticum aestivum* L.) used for early-season animal grazing and late-season grain production in the Southern Great Plains of the United States. Besides, in the chapter, the current production status and needs, the drawbacks of current cultivars, breeding strategies of the crop, novel genomics tools, and sensor technologies that can be used to improve dual-purpose winter wheat cultivars were presented. We will focus on traits that are, in general, not required by cultivars used for grain-only production but are critical for cool-season forage production.

Keywords: seedling vigor, regrowth vigor, grazing tolerance, seedling drought and heat stress tolerance, forage yield, grain yield, winter wheat

1. Introduction

Wheat (*Triticum aestivum* L.) is an important crop grown not only for grain in the world but also for forage production in some countries, such as the United States, Argentina, and Australia, during the cool-season months [1–4]. It is a good source of high-quality forage when other forage species are low in quantity and quality [5]. In the Southern Great Plains of the United States, especially in Oklahoma and Texas, winter wheat is often grown as a dual-purpose crop for both forage and grain production.

According to the United States Department of Agriculture (USDA)'s National Agricultural Statistics Service, about 9–11 million acres of winter wheat were planted annually in Oklahoma and Texas, but a significant portion of them were not harvested because of being used as winter pasture or poor production (**Table 1**). However, we were not able to get the precise acreage estimate of dual-purpose winter wheat that has been grazed over winter but still harvested for grain. According to a survey, approximately 40% of wheat acreage in Oklahoma was utilized as dual purpose for both forage grazing and grain production [5].

Compared to a grain-only production system, wheat used for winter grazing is often planted several weeks early, when air temperature is still high in the autumn. However, dual-purpose winter wheat often encounters seedling establishment challenges because of an excessive period of biotic and abiotic stresses resulting from early planting. In addition, wheat planted for forage also suffers grazing stress.

Year	Oklahoma		Texas	
	Planted (million acres)	Harvested (million acres)	Planted (million acres)	Harvested (million acres)
2010	5.2	3.9	5.7	3.8
2011	5.1	3.2	5.3	1.9
2012	5.4	4.3	5.6	2.9
2013	5.6	3.4	6.3	2.4
2014	5.3	2.8	6.0	2.3
2015	5.3	3.8	6.1	3.6
2016	5.0	3.5	5.0	2.8
2017	4.5	2.9	4.7	2.4
2018	4.3	2.0	4.7	1.6

Source: Crop production (May 2018), USDA, National Agricultural Statistics Service, Southern Plains Regional Field Office.

Table 1.
Winter wheat planted and harvested annually in Oklahoma and Texas.

Therefore, dual-purpose wheat cultivars should adapt to early planting and animal grazing. In this chapter, we will discuss the traits that are critical for dual-purpose winter wheat cultivars and how they could be improved.

2. Wheat cultivars used for dual-purpose production

The best cultivars for grain-only production may not be the best for dual-purpose production; therefore, it is crucial to select cultivars that are suitable for a grazing and grain system. Winter wheat cultivars planted in the Southern Great Plains of the United States show significant variation in forage yield [6]. Wheat cultivars that are suitable for grazing and grain should demonstrate both high forage yield and grain yield with tolerance to grazing stress and various other seedling stresses, such as heat, drought, disease, and insect stresses.

However, most current winter wheat cultivars being grown for dual-purpose use were developed for high grain yield and quality [7]. Autumn-winter forage yield, early-planting-associated seedling stresses, grazing tolerance, and regrowth ability have never been the focus of breeding programs because (1) forage yield is often negatively correlated with grain yield, (2) early planting stresses such as seedling heat and drought stresses may not be well evaluated because of climate variability of growing seasons, and (3) evaluation of grazing tolerance and forage yield is quite challenging because of lack of grazing facilities for effective grazing response selection in most wheat breeding programs. A common practice used in developing dual-purpose wheat cultivars is to use simulated grazing (i.e., clipping), which is very different from animal grazing in terms of grazing stresses encountered by the crop [5]. Therefore, proper breeding approaches should be followed to develop cultivars that have competitive autumn-winter forage yield while maintaining comparative grain yield. In addition to many agronomic traits that are generally required for grain production, wheat cultivars ideally grown in dual-purpose production systems should have seedling drought and heat stress tolerance, robust early seedling vigor, regrowth vigor, grazing tolerance, and Hessian fly (*Mayetiola destructor*) resistance.

3. Management practices of dual-purpose winter wheat

3.1 Early planting for increased forage yield

When moisture is available, early planting increases autumn biomass production. In the Southern Great Plains of the United States, farmers can grow winter wheat for forage-only, grain-only, or both forage and grain production [8]. Wheat used for grazing (forage-only or dual-purpose wheat) has been typically planted in early September, while wheat for grain-only production is planted in October. Planting in October minimizes disease and insect infestation, which is prevalent on early-planted wheat [9]. Disease and insect infestation on early-planted wheat can adversely reduce grain yield. There is generally a trade-off between forage production and grain yield when choosing a planting date. Previous research showed that planting 2–4 weeks earlier than the planting date of grain-only wheat can significantly increase autumn forage production by extending the vegetative growth period. In contrast, delaying planting (from September 10 to 30) has shown to increase grain yield by 18% but reduce forage production by 68% because the crop does not get enough time before winter to accumulate forage biomass [5]. Therefore, the focus of improving wheat for dual-purpose production is to develop cultivars with increased forage production while minimizing grain yield loss trade-off after grazing.

3.2 Proper grazing management to minimize grain yield loss

In a dual-purpose wheat production system, ideal grazing management is the key to ensure both high forage yield and high grain yield because grazing has shown to reduce the number of plant tillers, which are crucial for grain production after grazing. In general, grazing starts at least 60 days after planting, when the crown root system is fully developed, to prevent wheat plants from being uprooted by grazing animals [10]. Therefore, whole-plant sampling should be done to assess root development before cattle grazing is initiated. Estimated forage yield at grazing initiation is approximately 1700 kg DM/ha. Depending on the environmental conditions, grazing is done in the autumn, spring, or both. However, overgrazing should be avoided to prevent winterkill and reduced grain yield [10]. Grazing should be terminated when green canopy cover falls below 50% in autumn and 60% during late winter. Green canopy coverage is crucial for recovery from grazing, to maintain sufficient photosynthetic activity for increased forage biomass and grain production [11].

As a general recommendation, grazing must be stopped no later than the first hollow stem (FHS) stage, a growth stage in which hollow stem is visible above the root system and below the developing head [5]. Failure to stop grazing after FHS results in significant grain yield losses because of the damage to the reproductive structures by grazing [7, 8, 11–14]. Fieser et al. [11] found that grazing 2 weeks after the first FHS reduced grain yield by 10%, with an additional 10% each week, thereafter. Therefore, dual-purpose winter wheat cultivars with late FHS development will extend the grazing period during spring.

3.3 Other management practices for a successful dual-purpose production system

Other management practices, such as increased seeding rates and increased fertilizer rates, should also be considered to ensure a productive dual-purpose system. Greater seeding rates can not only increase forage yield but also stabilize grain yield, as some plants and tillers are lost from cattle trampling during grazing. When winter wheat is used for grazing, seeding rates (112–135 kg ha^{-1}) should be 50–100% greater than that of wheat grown for grain only (65–85 kg ha^{-1}) [15, 16]. Similarly, increasing fertilizer application rates for nutrients essential to plant growth, such as nitrogen (N) and phosphorus (P), is crucial for the success of dual-purpose winter wheat [16]. Grazing tends to deplete nutrients, such as N and P, accumulated in the aboveground biomass; as such, it is a general practice to increase fertilizer application rates for wheat grown for grazing. Nitrogen is one of the most important nutrients, which plays a significant role in regrowth after grazing [17]. Phosphorus application at planting has also shown to increase tillering and forage yield [16]. A common practice is to apply fertilizer nutrients at or before planting; however, care should be taken to not over apply and damage wheat seedlings. A general recommendation is to apply 56 kg ha^{-1} of diammonium phosphate (DAP, 18-46-0) by either banding or broadcasting at planting, or by topdressing after plants have completely covered the ground, followed by topdressing with an additional 56 kg ha^{-1} of N fertilizer (urea 46-0-0 or urea ammonium nitrate 33-0-0) when grazing is stopped. Soil sampling before planting to test for pH and available soil nutrients is helpful in determining the amount of nutrients needed [16].

Early planting also increases the potential risk from damage associated with insects. Fall armyworm (*Spodoptera frugiperda*) can be especially devastating to early-planted wheat [18]. Fall armyworm does not overwinter in Oklahoma; however, moths are typically blown north by the predominant southern winds during the early fall season and can lay eggs that hatch into larvae that consume forage [18]. Wheat seedlings not yet tillered are most at risk since the larvae can consume the forage to ground level and the seedlings are not able to regrow. The fall armyworm lifecycle completes in 3–4 weeks; thus, several generations can hatch before frost [18]. Scouting early and often is recommended until a killing frost has occurred. As a general rule, pesticide application to control fall armyworm is required about 40% of the time. Larvae populations can be highly concentrated and sporadic, so pesticide applications are often necessary only along the field perimeters or where moths first land. A treatment threshold is two to four larvae per linear foot of row, and greater control is achieved in small larvae [18].

Early-planted wheat is also at increased risk from sucking insects such as Hessian fly, Russian wheat aphid (*Diuraphis noxia*), and wheat curl mite (*Aceria tosichella*). These insects are not particularly damaging themselves; however, they are vectors for various viruses, such as *Wheat streak mosaic virus*, and *Triticum mosaic virus*, which can be potentially devastating for grain production [19] although causing minor loss in forage yield. Control measures are limited, as few tolerant varieties are available and pesticide applications are typically ineffective. Typical control is achieved from later planting dates and maintaining “green-free” fields for a minimum of 14 days before planting; however, these control measures are often not used when wheat is grown for forage.

4. Improving traits of wheat cultivars desirable for dual-purpose production systems

4.1 Seedling drought and heat stress tolerance

In the Southern Great Plains of the United States, farming is generally water-limited, as drought occasionally occurs and impacts the whole agricultural system. Wheat grown for dual-purpose use often encounters seedling establishment challenges because of drought and heat stresses at the seedling stage. According to current climate predictions, water will become scarce by the year 2025 and more farming land will be drought-stressed [20]. Previous studies have found yield losses associated with drought stress during the early vegetative growth of wheat to be as high as 79.7% [21, 22]. During the seedling stage, the stress can reduce the photosynthetic activity and respiration rate of seedlings, eventually causing them to die because of excessive dehydration [23–25].

Similarly, heat stress continues to be a pressing challenge to the crop. It is anticipated that the average global temperature will increase by 1–4°C by the end of the twenty-first century [26]. Heat stress affects the growth and development of wheat by impairing its morphological, physiological, and biochemical processes [24, 27–31]. The stress can impair the thylakoid membrane and photosystem II, a very important compartment of the plant cell involved in photosynthetic activity [23, 32, 33]. Therefore, development of seedling drought- and heat-tolerant cultivars is crucial for wheat being used in dual-purpose production systems in the region.

The two stresses at seedling stage are very difficult to phenotype under field conditions because of their genetic complexity, weather variability, interaction between the two stresses, and interaction with the environment. Generally, manual phenotyping of the stresses is tedious and time-consuming; in addition, stress response and data quality largely depend on plant growth and weather conditions. For this reason, marker-assisted selection (MAS) of the traits should be adopted once quantitative trait loci (QTLs) or genes are identified.

To date, QTL studies for drought tolerance have focused on either the flowering or the grain-filling stage of wheat [34–38] with few studies being done at the seedling stage. Similarly, QTLs for heat tolerance during the vegetative or the grain-filling stage have been discovered [32, 39, 40]. Recently, a QTL study for seedling heat tolerance was conducted under controlled growth chamber conditions using winter wheat cultivars collected across the Great Plains of the United States [41]. This study detected multiple QTLs in different chromosomes spreading across the wheat genome [41]. The molecular markers identified to date will facilitate the selection of seedling drought and heat tolerance during dual-purpose wheat breeding.

4.2 Early-seedling vigor and regrowth vigor

Robust early-seedling vigor and regrowth vigor traits are important for both forage and grain production because early-seedling vigor indicates the initial forage yield, while regrowth vigor reflects grazing tolerance and grain yield potential [5, 10]. For example, one previous study reported improved dry matter accumulation and grain yield from wheat lines with strong early-seedling vigor [42]. Over the years, seedling height and dry biomass weight have been used as good indicators of early-seedling vigor in different crop species, including wheat [43], maize (*Zea mays*) [44], and rice (*Oryza sativa*) [45]. In addition, early-seedling and regrowth vigor traits enhance the competitive ability of cultivars against invading weed species.

However, phenotyping early-seedling and regrowth vigor traits using phenotypic selection under field conditions is challenging because the traits are polygenic in nature and they are very hard to characterize. Therefore, identification of reliable molecular markers associated with the traits would facilitate cultivars' development using MAS. Currently, little research is being done to understand the genetic architecture of the early-seedling vigor and regrowth vigor that are negligible to grain-only production systems but crucial to cool-season wheat pasture in dual-purpose production systems. In addition, there is a need to employ high-throughput phenotyping technologies to characterize early-seedling vigor and regrowth vigor. Recently, unmanned aerial vehicles (UAVs) have been developed and adopted for use in large-scale phenotyping. However, the UAVs are not amenable to capturing high-resolution images of small plants such as seedlings because they were designed to fly at specified altitudes above the ground, making it difficult to record detailed information for small plants [46, 47]. Alternatively, small plants can be characterized using ground-based automated platforms at high-throughput phenotyping scales [48–50]. Image-based phenotyping offers a feasible tool to capture high-resolution images for evaluating seedling traits. Therefore, MAS and high-throughput phenotyping methods should be adopted to improve breeding efficiency of dual-purpose wheat cultivars with desired early-seedling vigor and regrowth vigor.

4.3 Grazing tolerance

Grazing tolerance is an important trait for sustainable production of autumn-winter forage biomass under forage-only and dual-purpose management systems. This trait is even more complex in nature; as such, it is extremely difficult to evaluate under field conditions. Presently, little work has been done to understand and to assess grazing tolerance in wheat. In alfalfa (*Medicago sativa*), grazing tolerance involves many interrelated morphological and physiological traits that interact with grazing activities and environmental conditions [51, 52]. Over the years, grazing tolerance has often been assessed by the survival of the plants after grazing or simulated clipping. However, evaluation of grazing tolerance using simulated clipping has not been successful in alfalfa [51, 52]. Counce et al. found no correlation between alfalfa's response to clipping and its response to grazing [52]. These studies concluded that the best way to phenotype grazing tolerance is to expose plants to stresses caused by the grazing animals rather than by simulated grazing [53]. The same principal could be applied to selecting grazing tolerance in wheat. However, most wheat breeding programs do not use grazing tolerance as a selection trait during the early stages of cultivar development because of limited grazing facilities.

Selection of grazing-tolerant plants is more effective under continuous stocking compared to selection based on morphological traits [51]. The "standard test protocol," whereby intensive grazing was incorporated with continuous stocking, was developed in alfalfa [51]. This protocol is currently used in phenotyping grazing tolerance by both public and private alfalfa breeders and in cultivar evaluation programs in the United States and other countries. However, it is still uncertain whether this protocol is applicable to the annual crop wheat. To date, there is no reliable phenotyping method that can efficiently assess variation in grazing tolerance during dual-purpose wheat breeding. No molecular markers associated with grazing tolerance have been identified for use in MAS. Therefore, QTL mapping or marker-trait association of grazing tolerance is needed before MAS becomes a feasible tool in selecting grazing tolerance of dual-purpose wheat.

4.4 Hessian fly resistance

The Hessian fly is one of the most destructive pests of wheat in the world, including the dual-purpose-wheat-growing areas in the Southern Great Plains of the United States. The fly can significantly reduce grain yield and quality by damaging leaves and stems of wheat in fall and spring. Its outbreaks have become more common in the last decade [54]. The fly preferably attacks wheat, but other cereal crops can also be the hosts [55].

Over the years, fly-free planting dates have been identified in some wheat-growing areas of the United States for managing Hessian fly. Wheat planted after the fly-free date is less likely to be infested [55]. However, it is impractical to delay planting for wheat grown for winter grazing in dual-purpose production systems. Although Hessian fly populations can be controlled by management practices such as stubble destruction and crop rotation, growing varieties resistant to the fly is the most economical strategy [55].

In the dual-purpose-wheat-growing areas, the chance of a Hessian fly outbreak is much greater than in areas growing wheat for grain only because of the extended growing season resulting from early sowing. No-till practice also increases the risk of widespread Hessian fly occurrence in general [55]. Therefore, developing cultivars that are resistant to the fly is critical for securing wheat production.

During the last two decades, great progress has been made in identifying Hessian fly biotypes, mapping and transferring resistant genes, characterizing resistant germplasm, and developing genetic markers for MAS [54–58]. To date, at least 18 Hessian fly biotypes have been classified, and at least 34 Hessian fly-resistant genes have been described in wheat and its relatives [57]. A few major resistant genes have been precisely mapped and effectively used in breeding wheat cultivars resistant to the Hessian fly using MAS [57, 58]. As selecting genotypes resistant to the Hessian fly is impractical in the field, MAS will be the most effective approach in breeding wheat cultivars resistant to the fly, and it has become a common practice in several wheat breeding programs in the Southern Great Plains of the United States.

4.5 Other traits significantly affecting grain yield

Besides the major traits discussed above that could significantly affect forage yield, winter wheat should also have a package of comprehensive traits required for grain production. The common traits that significantly affect grain yield and quality include resistance to various diseases and pests, tolerance to various abiotic stresses, lodging resistance, and high grain yield and quality. The most common diseases and pests include powdery mildew, leaf rust, stripe rust, *Wheat streak mosaic virus*, *Fusarium* head blight, wheat curl mite, greenbug, and Russian wheat aphid [59], and the most common abiotic stresses are drought and heat stresses at the flowering and grain-filling stages. Most of these traits have been the focuses of QTL or gene mapping in the wheat research community, and diagnostic molecular markers are available for MAS [59]; thus, they are not the focus of this chapter.

5. Adopting novel technologies to improve wheat cultivars desirable for dual-purpose production systems

5.1 Genomic tools

Plant breeders have attempted to use genomic markers to increase selection efficiency and accelerate breeding cycles. Molecular markers facilitate selection of important traits or genes that are interesting to breeders; thus, they play a major role in the genetic improvement of crop plants [60, 61]. In wheat, a vast number of QTLs or genes have been mapped, and markers tightly linked to the genes have been validated for MAS [59]. Marker-assisted selection has been very useful for selecting some traits that are hard to phenotype in the field. However, markers being used in breeding are still restricted to traits that are controlled by major genes, which have relatively large effects [59]. Unfortunately, only rarely have studies been done on forage-relevant traits, such as seedling drought and heat tolerance, early-seedling vigor, regrowth vigor, and grazing tolerance, which are critical for forage yield in dual-purpose production systems. Therefore, QTL mapping or marker-trait association of forage traits needs to be conducted for MAS in dual-purpose wheat breeding. The recent release of the wheat reference genome sequence [62] will undoubtedly accelerate marker discoveries of any traits that are of interest.

As most forage traits, such as grazing tolerance, are very complex in nature, genomic selection (GS) could be a good alternative option in dual-purpose wheat breeding. Genomic selection is a form of MAS whereby the breeding values of individuals with only genotype data are predicted using marker effects estimated from individuals with both genotypes and phenotypes from a training population. Although MAS is considered more efficient than phenotypic selection [63, 64], it has not been effective for complex traits [65]. In addition, MAS is not applicable across populations with different genetic backgrounds, and it requires significant efforts in marker-trait analysis to identify large-effect QTLs. In contrast, GS does not require marker-trait analysis, and it is suitable for complex traits. Therefore, GS is regarded as a better option than MAS [66, 67].

Moreover, GS has shown to improve genetic gain, reduce phenotyping costs, and accelerate the development of new cultivars by reducing the selection cycle [68]. So far, a number of GS models, including ridge regression best linear unbiased prediction (RR-BLUP) [69], Gaussian kernel (GAUSS) [69], and Bayesian LASSO (least absolute shrinkage and selection operator) [70], have been developed. Studies of the GS models in forage traits of dual-purpose wheat showed moderate to high prediction accuracies, ranging from 0.34 to 0.74, suggesting that at least some of the forage traits can be predicted with acceptable accuracy in wheat breeding (Maulana et al., unpublished data). Therefore, given the complexity of the forage traits to be selected and resource limitation, GS provides an alternative approach to facilitate trait selection during dual-purpose winter wheat breeding.

5.2 Sensor technologies for phenotyping forage yield traits

Forage biomass yield is one of the major target traits to improve in dual-purpose wheat breeding. However, manual phenotyping of the forage yield by harvesting and weighing forage samples at field breeding scales is not amenable in practice. Physical measurements of plant height and biomass estimation in different forage species have been performed using rising plate meters, capacitance meters, and meter sticks [71–74]. However, not only are these methods laborious and time-consuming, but it is also difficult to develop a reliable estimation model with them [75].

Recently, remote sensing has been developed and used successfully to predict plant height and forage biomass using ultrasonic, laser, and spectral sensors in different forage species [75–78]. The remote sensors greatly facilitate biomass estimation in field breeding because they are able to estimate biomass of a large sampling area within a short period of time. One of the parameters that has been most commonly used to predict biomass is the normalized difference vegetation index (NDVI). Normalized difference vegetation index has been employed in biomass estimation in several crops, such as wheat, maize, rice, bermudagrass (*Cynodon dactylon*), and alfalfa, with correlations between NDVI and biomass ranging from 0.52 to 0.84 [79]. These correlations suggest that NDVI is a good predictor of aboveground biomass. The prediction accuracies can be further increased when prediction models incorporate NDVI with proximal sensors, such as ultrasonic and laser height measurements [75].

In addition, forage nutritive values can also be predicted by modeling plant crude protein (CP) contents using a hyperspectral passive spectrometer [80]. Forage quality analysis has often been performed using near-infrared spectroscopy (NIRS) [81]. Positive high correlations were observed between CP measurements from NIRS and CP estimates from a hyperspectral reflectance model in wheat, bermudagrass, and tall fescue [80]. Therefore, sensor phenotyping platforms greatly increased the breeding efficiency, and facilitated the selection of forage biomass and quality traits during dual-purpose winter wheat breeding.

6. Summary

Winter wheat is an important crop grown in the Southern Great Plains of the United States. It is often grown for grazing during the cool-season months, when most forage species are not productive, and for grain under a dual-purpose or grain-only management system. The profit of managing wheat as a dual-purpose crop is usually better than managing it as a grain-only or forage-only crop when growing conditions are favorable because of alternative income options from livestock and/or grain. However, winter wheat cultivars grown for dual-purpose use are mostly developed for high grain yield only. Therefore, there is a need to develop wheat cultivars desirable for dual-purpose production systems in the region. The traits, such as seedling vigor, seedling tolerance to various stresses, and grazing tolerance, highlighted in this chapter, in general, are not required by or not important for cultivars used for grain-only production, but they are critical for cultivars desired for both cool-season grazing and end-season grain yield in dual-purpose production systems. Novel genomics tools will provide resources to increase the selection efficiencies of complex forage traits, and sensor technologies will significantly facilitate large-scale field phenotyping and selection. Therefore, it is expected that winter wheat cultivars can be improved desirably for dual-purpose production systems in the Southern Great Plains of the United States.

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Conflict of interest

The authors declare no conflicts of interest.

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