Chapter 6
Native Grasses for Biomass Production at High Elevations

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Abstract Herbaceous perennial grasses as lignocellulosic resources are a preferred feedstock source for biofuels because they have a neutral carbon budget, require few agronomic inputs, can be readily managed to be environmentally friendly, and have the potential to be grown on a variety of lands, soils, and crop production situations. The Mountain West at elevations of 1,200 m, and higher, typically have unique and variable conditions typified by dry climates, cold-season precipitation, cold winter temperatures, hot summers with cool nights, large areas of public land, long distances to markets, large variations in soil types, variable soil quality such as salinity, changing field topography, and other factors. Large regions of the Mountain West are dominated by cool-season grasses that could be a desirable source for biofuel production. Tall-statured, cool-season perennial grasses including basin wildrye, creeping x basin wildrye hybrids, intermediate wheatgrass, and tall wheatgrass are viable candidates for lignocellulosic biomass production in this region. Developing a locally grown biomass and biofuel products could provide economic diversification to rural communities in the Mountain West. Establishing a regional supply chain for biofuel production could diversify fuel sources and provide a degree of energy security. Cool-season biomass grasses are not currently cost-competitive with other biomass feedstocks or other Mountain West energy sources. Policies that encourage market development, energy diversification and security could jump-start the market for cool-season biomass grasses, although long-term market viability hinges on their production at competitive costs. Furthermore, commercial production of cool-season perennial grass species will require considerable genetic improvement to develop these plant species for suitable biomass production.

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Introduction

Considerable interest has focused on producing plant biomass for conversion into biofuels for the USA. Many biomass crop specie candidates and biomass resources have been proposed in recent years. Herbaceous perennial grasses as lignocellulosic resources are a preferred feedstock source for biofuels because they have a neutral carbon budget, require few agronomic inputs, can be readily managed to be environmentally friendly, and have the potential to be grown on a variety of lands, soils, and crop production situations. Plant species and their associated crop production systems used for sustainable biomass crop production have a number of requisites that should be taken into account when considering crop selection for commercial biomass production (Table 6.1).

Much of the popular and scientific attention on plant biomass has been centered on warm-season grasses with their production being located primarily in the Great Plains, midwest, and areas of the east and southeast USA where these warm-season grasses are adapted. Accordingly, a considerable amount of breeding and genetic research on the development of dedicated energy crops in the USA has been directed on warm-season perennial grasses, such as switchgrass (*Panicum virgatum*) and *Miscanthus* sp.

Large regions of the Mountain West in the USA are dominated by cool-season grasses. In a study conducted in Utah comparing the performance of warm- and cool-season grasses for biomass production, cool-season grasses were found to be the most productive for total annual biomass production [1]. Elevations of 1,200 m,

Table 6.1 Prerequisites of plant species used for biomass production for biofuel

High yields in comparison to inputs	Low-input production requirements
Does not compete with established food/feed systems or for established food/feed cropland	Drought tolerant with high water-use efficiency/low water-use requirements
Should be carbon neutral and preferably carbon negative	Facilitate mechanical harvesting and processing
Have desirable sociological aspects	Perennial growth and long-lived
Little allocation of dry matter to reproduction	Not weedy
Low moisture content at harvest	Minimum plant-to-plant competition
Good competition against weeds	Must be profitable to agriculture and others
Resistant against diseases and insects	Inexpensive and easy to plant and establish
Have positive environmental characteristics	

or higher, in the Mountain West typically have unique and variable conditions typified by dry climates, cold-season precipitation, cold winter temperatures, hot summers with cool nights, large areas of public land, long distances to markets, large variations in soil types, variable soil quality such as salinity, changing field topography, and other factors. Although the average annual precipitation is relatively low, seasonal climate patterns often provide adequate soil moisture and temperatures for cool-season perennial grasses in the spring and early summer. Specific areas of this highly varied region provide ideal growing conditions for tall-statured cool-season grasses.

The higher-elevation environments in many areas of the Mountain West are limited by the number and type of crops they can produce. Nevertheless, crops and cropping systems needed to produce low-input herbaceous perennial crops to support a bioenergy economy in the Mountain West are essentially unknown, especially for large-scale production [2].

Recent policies such as the Energy Independence Security Act of 2007 (EISA) and the second US Renewable Fuel Standards (RFS) have targeted biofuel production and domestic energy independence. In contrast to most of the country, the Mountain West has attracted few biorefineries (http://www.ethanolrfa.org/bio-refinery-locations/) and is not expected to provide abundant biofuel development [3]. From a cost standpoint, this is not unexpected, due to high-input costs associated with irrigation water for production and transportation costs of biomass [4, 5]. Overcoming transport distances and water requirements are considered to be especially challenging for Mountain West biomass production [6]. The arid western states are not expected to provide abundant biofuels due in large part to the difficulty of identifying biomass crops that can sustain success in an arid setting. However, despite the low EISA projections for the region, energy disruptions and high energy prices would also presumably affect the Mountain West. Biomass crops that facilitate energy security on farms in the Mountain West benefit the region as a whole and make the RFS goals more attainable. Irrespective of the EISA biofuel mandates and policy targets, if bioenergy crops (grasses or oilseeds) are shown to be economically feasible for agricultural producers, their commercial production, and subsequent market development will result.

This chapter is intended to contribute towards developing biomass crop production and biofuel markets in the Mountain West with a focus on the potential of cool-season perennial grass species for biomass production and on modeling the profitability of agronomic production of perennial grasses. Tall-statured, cool-season perennial grasses including basin wildrye, creeping x basin wildrye hybrids, intermediate wheatgrass, and tall wheatgrass are viable candidates for lignocellulosic biomass production in this region. While this chapter is charged to focus on native grasses, we have arguably included grass species that are not native but have historically been grown in the USA and have been widely used in many applications. Based on their historic use over a sustained period of time, they are considered to be naturalized. These naturalized species along with native grass species have merit for consideration in biomass/bioenergy applications.

Basin Wildrye

Taxonomy and Domestication

Basin wildrye (*Leymus cinereus* (Scribn. & Merr.) À. Löve), also known as Great Basin wildrye, includes grasses previously treated as *Elymus cinereus* Scribn. and Merr. Creeping wildrye (*Leymus triticoides* (Buckley) Pilg.), also known as beardless wildrye, includes grasses previously treated as *Elymus triticoides* Buckl. Basin and creeping wildrye are closely related species of the tribe Triticeae genus *Leymus*, which encompasses about 50 perennial grass species from temperate regions of North America, Europe, and Asia [7]. Of the 17 *Leymus* taxa in North America, four species are introduced, two are naturally occurring hybrid taxa, and 11 species including basin wildrye and creeping wildrye are native [7, 8]. Both basin and creeping wildrye are highly self-sterile ([9]. The most obvious differences between these two species is that basin wildrye is generally taller (up to 270 cm) strictly caespitose with few if any short rhizomes, whereas creeping wildrye is typically shorter (usually less than 125 cm) and strongly rhizomatous [7, 10]. Basin wildrye also has relatively large spikes, up to 29 cm long, with 2–7 spikelets per node, whereas creeping wildrye also has smaller spikes with 1–3 spikelets per node. Hybrids between creeping and basin wildryes occur naturally in regions of overlapping distribution, but have not been formally named [7]. Basin and creeping wildrye are the only native *Leymus* wildrye species cultivated for seed or forage in the western USA. Cultivars and germplasms of basin and creeping wildrye have been developed from natural collections [11–14]). Seeds from at least several *Leymus* wildrye species, including basin and creeping wildryes, have been utilized as food grains by Native Americans of California and the Great Basin, Vikings, and other human societies [14–16]. There has been some effort to domesticate mammoth wildrye (*Leymus racemosus* (Lam.) Tzvelev) and beach wildrye (*Leymus arenarius* (L.) Hochst.) as perennial grain crops [15]. However, neither basin nor creeping wildrye can be considered fully domesticated.

Areas of Production

Basin and creeping wildryes are both native to western North America. Basin wildrye is widespread throughout this region including Alberta, northern Arizona, British Columbia, the California Sierra-Nevada, Colorado, Nevada, Montana, Washington, and Wyoming [7, 16]. Like most *Leymus* species, basin and creeping wildryes are well adapted to alkaline soils and cold-growing environments of this region. Although basin wildrye can be found throughout a wide variety of desert and mountain habitats, large native stands are typically restricted to specific areas where soil and water accumulate including roadsides and irrigation borders. Very few native species are so equally well adapted to both saline soils of the desert basins and nonsaline soils of the upland sagebrush/grassland environments [17]. Basin wildrye was presumably once abundant on more productive soils of the intermountain valleys and floodplains that are now cultivated croplands and pastures [16]. Basin wildrye supplements tall wheatgrass in saline pastures, where it is grazed in the spring and fall [18–20], and provides valuable forage for winter grazing across western rangelands [16, 21, 22]. Basin wildrye is primarily used for large-scale rangeland rehabilitation, erosion control, and other conservation uses throughout western North America [23]. It is recommended for areas receiving 250–400-mm precipitation [21], but is often found growing in drier saline desert basins where surface or subsurface moisture may accumulate [24–26]. Basin wildrye has demonstrated tolerance to phytotoxic soils contaminated by heavy metals and is one of the more useful native grasses for mine reclamation in the western USA [27–30]. Although crops and forages grown on contaminated soils may pose health risks to humans and livestock, these areas may be suitable for biofuel production if the contaminants can be properly managed.

Creeping wildrye is commonly found on harsh alkaline sites in California, Nevada, Utah, and southeast Oregon [7, 21]. Creeping wildrye may have been one of the dominant species in the prairies and lowland oak woodlands of the California Central Valley [31]. Creeping wildrye is primarily used for soil stabilization, especially along channel or river banks, and for wildlife habitat in wetland and riparian plantings [14]. It is also recommended for use as forage and for reclamation of croplands and pasturelands contaminated by saline irrigation water [14]. The salt tolerance of creeping wildrye approaches that of tall wheatgrass and both species are being evaluated for forage and biomass production using saline irrigation water in the San Joaquin Valley of central California [32–34].

Genetic Resources

Next to *Thinopyrum* (wheatgrass), species in the genus *Leymus* have been of greatest interest to Triticeae grain breeders since the early 1940s when N. V. Tsitsin initiated hybridizations between *Leymus* and the Triticeae cereal genera *Triticum*, *Hordeum*, and *Secale* [15, 35]. Several *Leymus* species have been successfully hybridized with wheat, and some of the resulting introgression lines display potentially useful traits including biological nitrification inhibition [36], resistance to *Fusarium* head blight [37–39], and salt tolerance [40]. The genus *Leymus* are comprised of allopolyploid member species that contain the **Ns** genome of *Psathyrostachys* (Russian wildrye) and the **J** genome of *Thinopyrum*, based on chromosome pairing of interspecific hybrids [35]. However, early cytogenetic experiments raised doubt on the putative genome relationship between *Leymus* and *Thinopyrum*, which led to the currently accepted **NsXm** subgenome designations where **Xm** is from an unknown diploid ancestor [41, 42]. In any case, it is should be relatively easy to hybridize species and transfer chromosomes or genes between congeneric *Leymus* species, but introgression between genomically defined Triticeae genera requires more sophisticated breeding and cytogenetic techniques [35, 43]. Most *Leymus* species are allotetraploid ($2n = 4x = 28$); however, octoploid ($2n = 8x = 56$) and duodecaploid ($2n = 12x = 84$) species and races exist. About 40 % of the surveyed basin wildrye accessions are tetraploid as are all creeping wildrye accessions [44]. However, the majority of basin wildrye accessions are octoploid.

Genetic markers and maps have been specifically developed for gene discovery and breeding research using hybrids of basin and creeping wildryes. Nearly 1,800 simple sequence repeat (SSR) markers were designed from 11,281 expressed gene sequence tags (ESTs) from creeping x basin wildrye hybrids [45]. Most of the 12,000 *Leymus* ESTs have been aligned to *Brachypodium*, and other grass genome reference sequences on the biofuel feedstock genomics resource from Michigan State University (http://bfgr.plantbiology.msu.edu/) and GrainGenes [46]. Three full-sib genetic mapping populations comprised of 586 progenies from reciprocal backcrosses of creeping x basin wildrye hybrids to creeping and basin wildrye testers were developed to map genes and markers associated with functionally important trait differences between these species [46–48]. Molecular genetic maps were constructed by genotyping these highly polymorphic mapping populations using nearly 2,000 DNA markers including 435 *Leymus* EST and 28 marker loci for nine of the ten known lignin biosynthesis genes. A large-insert bacterial artificial chromosome (BAC) libraries were developed from a creeping x basin wildrye hybrid including 405,888 clones with an estimated average length of 150.5 kb per insert, which represents 6.1 haploid genome equivalents of these allotetraploid *Leymus* wildryes [49]. These experimental plant materials and DNA libraries provide valuable tools for gene discovery research and plant breeding.

The USDA National Plant Germplasm System (NPGS) currently holds 242 accessions of basin wildrye and 20 creeping wildrye accessions. Three geographically significant landraces of basin wildrye were identified by DNA analysis of the NPGS accessions [44]. The Columbia race extends from British Columbia in the north, south through the Columbia River Plateau of Washington and Oregon, and further south into the Sierra Steppe of southeastern Oregon and northern California. About 91 % of the accessions classified in the Columbia race were octoploid. The Rocky Mountain race extends from the Rocky Mountain Piedmont of Alberta and Montana in the north; south through Wyoming, Utah, and Colorado; and west across the Snake River Plateau of Idaho and the Intermountain region of Nevada and Utah. About 82 % of the accessions classified in the Rocky Mountain race were tetraploid. The Great Basin race is interspersed with the Rocky Mountain accessions, but it is restricted to the Great Basin region of southwestern Idaho, Nevada, and western Utah. The Great Basin race is genetically more similar to the Rocky Mountain race, but like most of the accessions from the Columbia race, 73 % of the Mountain race accessions are octoploid.

Major Breeding Achievements

The octoploid ($2n = 56$) basin wildrye cultivar "Magnar," released in 1979 [11], is believed to have originated from southeastern British Columbia. The tetraploid ($2n = 28$) basin wildrye cultivar "Trailhead," originally collected near Roundup, Montana, was released in 1991 [12]. Cultivars Magnar and Trailhead represent the two most widespread and important genetic races, the Columbia race and Rocky Mountain race, respectively [44]. Magnar and Trailhead can be visually distinguished by the presence or absence of glaucous cuticle wax, which appears to be controlled by a single dominant gene orthologous to the wheat *Inhibitor wax* (*Iw*) gene [46]. Both Magnar and Trailhead have been widely used in seed mixtures with other grass species on public and privately owned rangelands of the western USA. "Continental" is a cultivar [50]) derived from a chromosome-doubled Trailhead pollinated by the natural octoploid, Magnar, which shows increased seed mass and seedling vigor compared to the parental cultivars [50]. The cultivar Continental segregates for the glaucous trait [50] and presumably segregates for other genes that distinguish its Columbia and Rocky Mountain parental races. The basin wildrye cultivar "Washoe" was collected from a natural population growing on phytotoxic soils near the now defunct Washoe smelter stack in western Montana, which is contaminated with arsenic, cadmium, copper, lead, and zinc [13].

The only creeping wildrye cultivar Rio, released in 1991, was originally collected in Kings Valley, California, and is used for soil stabilization in riparian areas, forage production, and reclamation of saline, irrigated croplands and pasturelands [14, 32]. Another cultivar, "Shoshone," was originally released as creeping wildrye, but morphological characters [21] and chloroplast DNA sequences [51] of Shoshone are similar to Eurasian *Leymus multicaulis* [14].

Breeding Strategies, Traits, and Goals

Growing up to 3 m tall [7, 10], basin wildrye has relatively high biomass accumulation potential, with up to 13,300 kg ha^{-1} observed with no irrigation or fertilizer in Cache Co., UT. Basin wildrye has a deep and extensive root system [52, 53]; high photosynthetic capacity, nitrogen-use efficiency, and intrinsic water-use efficiency [54]; and salt tolerance [24–26] that enable basin wildrye to maintain growth and physiological activity during dry summer periods when many other perennial grasses are dormant [54]. Basin wildrye tends to begin spring growth early, flower later, and stay green longer than other cool-season native perennial grasses, which extends the vegetative growth of this species [54, 55]. Biomass production can be enhanced from low levels of fertilization and irrigation, but once established it is a low-maintenance plant requiring little additional treatment or care [23]. These traits of basin wildrye can be useful for low-input biomass production in high-elevation environments of the Mountain West that are often favored by winter-precipitation patterns. However, the high growing point of basin wildrye is susceptible to clipping and grazing [23, 55, 56], and it is difficult to establish good stands due to poor seedling vigor [21]. The release of Continental basin wildrye demonstrates that there is sufficient genetic variation within the species to improve seedling establishment [50]. Moreover, interspecific hybridization is being used to introgress rhizome genes into basin wildrye [10], which is expected to improve its grazing tolerance. Basin wildrye is susceptible to black grass bugs, including *Irbisia pacifica* and *Labops hesperius*, which can decimate grass monocultures [57].

Poor seed fill, low germination, and weak seedling vigor are the major limitations of basin wildrye [21]. Although the relatively large spikes of basin wildrye can produce thousands of seeds, these seeds readily disarticulate from the spikelet rachilla [7] and are prone to seed shattering [58]. Basin wildrye seed production fields require close scrutiny to prevent seed losses and ensure complete physiological development of the caryopsis [23, 58]. Moreover, the timing of seed harvest may be complicated by the fact that individual plants are genetically variable and may show variation in the timing of flowering and seed development [10, 58]. Thus, it has been speculated that seed performance problems associated with basin wildrye may be partly attributed to the temptation to harvest seed before it is physiologically mature [58].

The potential of creeping wildrye as a forage or biomass crop is derived from its adaptation to moist saline-alkaline soils [34, 59]. The cultivar Rio produced between 10,000 and 13,800 kg ha^{-1} in fields with soil salinities of 12.9–21.0 dS/m EC_e [34]. Although creeping wildrye is a relatively poor seed producer and has dormant recalcitrant seeds and weak seedling vigor, this species is not prone to seed shattering [14, 58, 59]. Once established, the aggressive rhizomes of creeping wildrye rapidly spread to produce better coverage, provide exceptional resiliency to clipping and mowing, and typically survive for many years [14]. However, this species may lack the biomass accumulation potential of taller statured species such as tall wheatgrass or basin wildrye [48, 60]. Moreover, seed and forage production typically declines when stands are left to become sod bound.

Hybrids between creeping and basin wildryes are partially fertile, and it has been suggested that it may be possible to introgress simply inherited traits from one species to another [43]. In particular, Dewey [43] suggested that the seed germination of creeping wildrye could be improved by introgression of genes from basin wildrye and the growth habit of caespitose basin wildrye could be improved by introgression of rhizome genes from creeping wildrye. Likewise, Larson and Kellogg [58] suggested that introgression of a recessive gene variant that abolishes seed abscission from creeping to basin wildrye could be used to improve ripening and development of basin wildrye seeds. Moreover, the F_1 hybrids of creeping wildrye and basin wildrye hybrids display increased plant biomass, with up to 14,100 kg ha^{-1} observed with no irrigation or fertilizer in Cache Co., UT. The creeping and basin wildrye parents of this hybrid produced 4,600 and 9,600 kg ha^{-1} in the same experiment. Progeny of these hybrids display transgressive segregation for biomass, forage quality, and many other traits including rhizomes and seed retention [10, 60, 61]. These observations suggest possibilities of improving the biomass yield and composition; however, some of these traits may be multigenic or recessive making introgression by phenotypic selection difficult. Thus, genetic markers associated with seed retention [58] other important traits [10, 60, 61] can be used to introgress functionally important genes between these species with documented precision not possible by phenotypic selection alone. This approach of marker-assisted gene introgression is fundamentally based on conventional breeding techniques and natural processes. For example, some natural basin wildrye populations contain DNA alleles and traits, such as short rhizomes, which may result from introgression from natural hybrids between basin and creeping wildryes [7, 44]. However, the molecular markers enable selection of recessive genes, complementary genotypes, and other cryptic factors that are difficult to detect by conventional breeding procedures.

Seed Production

Methods of seed production for basin and creeping wildryes are well established, and rhizome sprigs can also be used to establish creeping wildrye in areas that are inundated by water or where rapid cover is needed [14, 23]. However, methods of seed production for creeping x basin wildrye hybrids have not been firmly established. The hybrids are partially fertile and synthetic populations derived from creeping x basin wildrye hybrids are being developed and tested at the tetraploid level [47] and colchicine-doubled octoploid level [62]. However, it is not clear if hybrid heterosis and fertility can be stabilized and maintained in synthetic populations that may be segregating for cryptic chromosome differences, which may cause problems with meiosis in later generations. Novel methods of producing F_1 hybrid seed of creeping and basin wildryes may be possible by taking advantage of the highly rhizomatous nature and strictly self-incompatible mode of pollination in creeping wildrye [9]. Creeping wildrye can be clonally propagated by rhizomes [10, 14], and it has been observed that some clones readily hybridize with basin wildrye especially if no other pollen source is available [47]. Thus, it may be possible to select and propagate a single creeping wildrye genotype, clonally, for use as a hybrid seed parent that would be pollinated by basin wildrye cultivars or populations.

Intermediate Wheatgrass

Taxonomy and Domestication

Under the present taxonomic treatment [63], intermediate wheatgrass (*Thinopyrum intermedium* (Host) Barkworth and D. R. Dewey) includes grasses previously treated as *Agropyron intermedium* (Host) Beaus., *A. trichophorum* (Link) K. Richt.

(pubescent wheatgrass), and *A. pulcherrimum* Grossh. Barkworth et al. [63] recognize two subspecies within intermediate wheatgrass subsp. *intermedium*, which is glabrous and subsp. *barbulatum* (Schur) Barkworth and D. R. Dewey, which is pubescent (syn. pubescent wheatgrass). Intermediate wheatgrass was first described from a collection in Yugoslavia in 1805 as *Triticum intermedium* by Host [64]. Intermediate wheatgrass spikes are borne on erect stalks and seeds are easily threshed, lending itself as a possible perennial grain crop on hilly or otherwise marginal land, thus reducing the farmers economic costs (i.e., labor and fuel) along with soil erosion (i.e., low-impact sustainable agriculture) [65]. Intermediate wheatgrass is tolerant of some saline soils, used as a fall and early winter forage [66], as well as providing an immense genetic reservoir to select from for disease and insect resistance in the cereals [67]. Intermediate wheatgrass is generally considered to be highly self-sterile, although self-fertile plants occasionally occur [9]. The first introduction (PI 20639) came into the USA from Trans Ural, Siberia, in 1907 [68].

Areas of Adaptation and Production

Intermediate wheatgrasses' natural distribution is found in steppes, on open stony and aleurite slopes among shrubs up to the lower mountain belts of southern Europe through the Middle East and southern USSR to western Pakistan [64, 69]. Dewey [68] reported that no intermediate wheatgrass collections have been recorded south of 30° north lat. and the more southerly collections were made only at higher elevations. Most collections within Iran were between 1,200 and 2,100 m.

In North America, intermediate wheatgrass is used for hay and pasture on sites receiving at least 35-cm annual precipitation at altitudes up to 3,000 m. It is widely distributed in the Intermountain Region and northern Great Plains of the USA and Canada where it grows best on well-drained, fertile soils that receive 30–46 cm of annual precipitation. It is recommended for sagebrush sites and high mountain areas up to 2,700 m. It is moderately tolerant of shade and alkalinity. As a general rule, intermediate wheatgrass is adapted to sites currently occupied by smooth bromegrass (*Bromus inermis* Leyss.). Yields and stand persistence can be increased in intermediate wheatgrass if grown with a legume. In drier areas (less than 38 cm of precipitation), intermediate wheatgrass yields more than smooth brome and crested wheatgrass [*Agropyron desertorum* (Fisch. ex Link) Schult]; however, after several years of harvesting, intermediate wheatgrass yields decline. The pubescent form is considered to be better adapted to the more southern limits of the species adaptive range in Asia [70] and the USA [71]. It appears to be better suited to droughty, infertile soils and saline sites that receive 30–35 cm of annual precipitation than typical intermediate wheatgrass [66].

Intermediate wheatgrass will outyield bromegrass and reed canary grass when grown on fertile well-drained irrigated land and will equal crested wheatgrass and outyield bromegrass under drought conditions on dryland. Under favorable conditions, intermediate wheatgrass will outyield both crested and bromegrass under moist years on dryland cites [72]. Intermediate is less competitive with alfalfa (*Medicago sativa* L.) than bromegrass or crested wheatgrass and maintains a more desirable grass-alfalfa balance. Smart et al. [73] reported that May to June forage of smooth bromegrass outyielded intermediate wheatgrass by 750 kg ha^{-1} during the first harvest season, but only by 275 kg ha^{-1} at the second harvest season. Across three locations in Nebraska, intermediate wheatgrass averaged 5,301 kg ha^{-1} and ranged from 3,801 to 6,401 kg ha^{-1} [74]. At Mead, NE, between 1986 and 1987, Manska intermediate wheatgrass averaged 7,201 kg ha^{-1} compared to 6,800 kg ha^{-1} for cultivars Oahe and Slate; however, by 1989, the overall biomass was twice that with differences between cultivars reported [75]. Black and Reitz [76] reported that with increased row spacing width from 76- to 152-cm biomass went from about 3,500 kg ha^{-1} to 3,100 kg ha^{-1} under fertilization (67 kg ha^{-1} N and 22 kg ha^{-1} P); however, under no fertilization biomass production remained at around 2,000 kg ha^{-1} regardless of row spacing width. Dry matter yields averaged over four test sites, and multiple years in North Dakota were 4,226, 4,228, and 4,509 kg ha^{-1}, respectively, for intermediate wheatgrass cultivars Manska, Oahe, and Reliant [77]. Rush intermediate wheatgrass cultivar ranked among the four highest entries for overall biomass yield across five irrigation levels, averaging 23,700 kg ha^{-1}, and was the single best entry at low-irrigation levels, 19,100 kg ha^{-1}, in a comparison of 21 warm-season and six cool-season grasses [1].

Intermediate wheatgrass has increased the productivity of marginal land where bromegrass and orchard grass (*Dactylis glomerata* L.) are not well adapted. Its water requirement is between smooth bromegrass and crested wheatgrass, and it flowers from 1 to 2 weeks later than these grasses. Because of its relatively late maturity and quality retention after frost, intermediate wheatgrass has been effectively used for grazing during the fall and early winter in the Intermountain Region.

Although intermediate wheatgrass is noted for its productivity, it is sensitive to mismanagement or intense defoliation. Early cultivars failed to persist more than 4–5 years and were not good seed producers, prompting many to prefer either smooth bromegrass or crested wheatgrass. However, these problems have been overcome through the development of improved cultivars [78]. The forage quality of intermediate wheatgrass also declines at advanced stages of maturity. Intermediate wheatgrass is sensitive to mismanagement at the time of harvesting in the shooting stage [79].

Genetic Resources

Species in the genus *Thinopyrum* [35] have been of the greatest interest to wheat breeders since the early 1930s when N. V. Tsitsin first demonstrated that *T. ponticum* (Podp.) Barkworth and D. R. Dewey, intermediate wheatgrass, and *T. junceum* (L.) Á. Löve hybridized readily with various species of *Triticum* [80]. Chromosome numbers in intermediate wheatgrass range from $2n = 42$ to 52 with the aneuploids arising from unequal chromosome disjunction or unreduced gametes. Its stable chromosome number is $2n = 42$ [81]. Based on chromosome pairing and C-banding patterns in intermediate wheatgrass, Liu and Wang [82] proposed that it is described as a segmental autoallohexaploid with the genomic formula of $\mathbf{E^eE^eE^eE^eStSt}$. Subsequently, Xu and Conner [83] described it as an allohexaploid $\mathbf{E^bE^bE^eE^eStSt}$ with its origin resulting from hybrids between diploid *T. elongatum* (Host) D. R. Dewey ($\mathbf{E^eE^e}$) or *T. bessarabicum* (Savul & Rayass) Á. Löve ($\mathbf{E^bE^b}$) and one of several tetraploid species *Elytrigia caespitosa* (C. Koch) Nevski ($\mathbf{E^eE^eStSt}$), *Elytrigia nodsa* (Nevski) Nevski ($\mathbf{E^eE^eStSt}$), and *Pseudoroegneria geniculata* (Trin.) Á. Löve ssp. *scythica* (Nevski) Á. Löve ($\mathbf{E^eE^eStSt}$).

A total of 1083 EST-SSR markers were developed from 16,128 Sanger DNA sequencing reads, with 6,450 contigs and 2,330 unmatched reads, of *Pseudoroegneria spicata* (**St St**) [45]. A total of 1,379,000 pyrosequencing reads, with an average length of 427 bp, were obtained from cDNA of hexaploid *Thinopyrum intermedium* ($\mathbf{E^eE^eE^bE^bStSt}$) and two diploid *Thinopyrum* species, *T. bessarabicum* ($\mathbf{E^b\ E^b}$) and *T. elongatum* ($\mathbf{E^e\ E^e}$), using next-generation techniques [84]. These short-read EST sequences were assembled into 71,300 contigs (667-bp average length), with 123,200 unmatched reads, containing an abundance of putative single-nucleotide polymorphisms (SNPs) and other possible DNA polymorphisms [84]. These *Pseudoroegneria* and *Thinopyrum* ESTs are being used to test and develop genome-specific EST-SSR markers and high-throughput SNP genotyping assays for intermediate wheatgrass.

The Montana-1 male sterile intermediate wheatgrass cultivar was derived from amphiploid hybrid *Triticum turgidum* L. var. *durum* x intermediate wheatgrass [85]. In 1986, the Montana Agricultural Experiment Station released Montana-2 perennial X *Agrotriticum intermediodurum* Khizhnyak resulting from a cross between durum wheat and intermediate wheatgrass. Seed of this hybrid is nearly three times as heavy as that of typical intermediate wheatgrass. It is proposed as a potential perennial grain crop in areas where soil erosion and production costs are limiting factors. The germplasm has potential as a genetic donor for disease resistance, winter hardiness, drought resistance, and semi-dwarfness in wheat breeding programs [86]. Subsequently, Jones et al. [87] concluded lines derived from Montana-2 contained individuals that could be used to improve biomass production if the population could be stabilized with improved seed production.

Within the National Plant Germplasm System (NPGS), there are 161 active collections of intermediate wheatgrass. The collections cover the following countries Afghanistan (5 accessions), Austria (1), Canada (1), former Soviet Union (17), Iran (83), Kazakhstan (21), Portugal (1), Russian Federation (8), Turkey (10), Turkmenistan (2), Ukraine (2), the USA (9), and Uzbekistan (1).

Breeding Strategies, Traits, and Goals

Accessions initially introduced into the USA failed to create significant interest for intermediate wheatgrass [78]. However, the introduction of PI 98568 from Maikop, USSR, in 1932 was the foundation for cultivar development in establishing intermediate wheatgrass as a forage grass in the USA. This PI was released as the cultivar “Ree” by the South Dakota Experiment Station and has contributed parental germplasm for the cultivars “Chief,” “Greenar,” Nebraska 50, “Oahe,” and “Slate.” Additional cultivars “Luna” (pubescent form) and Mandan 759 (pubescent form) were selected from PIs 106831 and 116252, respectively [21].

In 1966, the Canada Agricultural Research Station at Lethbridge released a 12-line synthetic cultivar “Greenleaf”, a pubescent wheatgrass type selected for increased seedling vigor, earliness of spring growth, forage yield, winter hardiness, predominance of bright green foliage, and pubescence of spikelets [88]. In 1980, the Research Station at Swift Current, Saskatchewan, released the cultivar “Clarke,” a 20-clone synthetic with breeding emphasis on drought tolerance, winter hardiness, good seed quality, and productivity of forage and seed [89].

The cultivars “Reliant” and “Manska” were released in 1991 and 1992, respectively. Reliant combines traits from 24 different hexaploid intermediate wheatgrass cultivars and experimental lines selected for improved persistence, forage quality, and forage and seed yields [90]. Manska was derived from Mandan 759 pubescent wheatgrass. It is particularly noted for its high nutritive value, based on in vitro dry matter digestibility (IVDMD) and animal performance [77].

In 1994, 2003, and 2003 cultivars “Rush,” “Haymaker,” and “Beefmaker” were released by Aberdeen Plant Materials Center (PMC) and the University of Nebraska, respectively. Rush was selected directly out of PI 281863 from Germany with emphasis on increased seedling emergence and plant vigor [91]. Haymaker originated from PIs 440015, 440008, and 440011 from the former USSR, and the cultivar Slate. Haymaker was selected for increased forage yields and in vitro dry matter digestibility [92]. Beefmaker intermediate wheatgrass is a broadly adapted cultivar that produces forage with high IVDMD and high protein concentration in the tallgrass, midgrass, and shortgrass ecoregions of the central Great Plains, USA. It was developed by intercrossing six plant introductions (PI 345586, PI 273733, PI 273732, PI 315353, PI 315067, and PI 3155355) that were identified as having superior agronomic performance in the central Great Plains in a germplasm evaluation [93]. The most recent cultivar release was “Manifest” in 2007 by ARS, NRCS – Bismarck, ND (PMC), and the North Dakota Agricultural Experiment Station. Manifest originated from ten collections near Stavropol and Svetlograd, in the Caucasian region of Russia collected by the late Douglas R. Dewey. It was selected for forage yield, seed yield, spring recovery, and resistance to leaf spot. Its higher tiller density results in improved persistence and stand longevity [94].

Seed Production

Intermediate wheatgrass spikes are borne on erect stalks, and seeds are easily threshed [95]. Because of its relatively high yield of large seed and vegetative characteristics, it has been proposed as a possible perennial grain crop in a low-impact sustainable agricultural system [96]. For optimum seed production, row spacing of 60 cm under irrigation and 90 cm under dryland conditions are recommended at a seeding rate of 9.2 kg ha^{-1} (irrigated) and 6.9 kg ha^{-1} (dryland). Seed fields should be planted in late summer by mid-August with adequate soil moisture or supplemental irrigation or early in the spring. If fall moisture and/or spring moisture is not reliable, then a fall-dormant seeding just prior to the soil freezing is recommended. Under irrigation, seed yield will range from 728 to 1,176 kg ha^{-1} averaging 952 kg ha^{-1}. When grown as a dryland crop, seed yields average 392 kg ha^{-1} and range from 224 to 560 kg ha^{-1}. Seed production fields remain productive between 5 and 10 years [97].

Tall Wheatgrass

Taxonomy and Domestication

Tall wheatgrass [*Thinopyrum ponticum* (Podp.) Liu and Wang] was previously treated as *Agropyron elongatum* (Host) Beauv., *A. elongatum* ssp. *ruthenicum* Beldie in North America, and as *Elytrigia pontica* (Podp.) Holub by Asian botanists [35]. The true *A. elongatum*, now excluded from *Agropyron* sensu stricta, is a diploid ($2n = 14$), while the robust grass known as tall wheatgrass in North America is a decaploid ($2n = 70$) [35].

Tall wheatgrass is indigenous to southern Europe and Asia Minor and was originally introduced into North America from Turkey in 1909 [98]. In its native habitat, it is often associated with saline or alkaline soils in meadows, salt marshes, and seashores [99]. It is a long-lived, coarse, vigorous, perennial bunchgrass with leaves that are long and erect. It is the latest maturing of the grasses adapted to the temperate rangelands of the west.

Areas of Adaptation and Production

Tall wheatgrass is one of the most saline or alkali-tolerant cultivated grasses and is particularly noted for its capacity to produce forage and persist in areas that are to alkaline or saline for other productive crops. On less favorable sites, e.g., saline and low moisture, it is short-lived unless there is a water table below the dry surface.

It can tolerate up to 1 % soluble soil salts. Tall wheatgrass increases production yields in soils with salinity levels of 6,000–18,000 ppm and persists in soils with electrical conductivity (EC) up to 26 mmhos/cm [100].

Tall wheatgrass is adapted to semiarid range sites receiving a minimum 35–40 cm of precipitation annually, or on irrigated or subirrigated soils at elevations from 1,300 to 1,850 m. In North America, it is widely used throughout the Mountain West and the northern Great Plains in salty areas in association with greasewood and salt grass. In the Columbia River drainage and the Great Basin, it competes well with native species such as basin wildrye on saline soils [101]. Tall wheatgrass has large seed that is easy to harvest and plant. It has good seedling vigor, and established plants have an exceptionally deep root system, which contributes to its resistance to drought [98, 102]. Under favorable conditions, it establishes as a dominant and may form a monoculture, thereby reducing diversity [101].

Tall wheatgrass remains green 3–6 weeks later than most other range grasses and is often valued as a source of forage during late summer, fall, and early winter [66]. It also has been used successfully as a silage crop. Because of its late maturity, it is usually recommended that tall wheatgrass be seeded alone. Leaving 20-cm stubble is recommended at year's end to prevent animals from grazing too close the following year. Grazing should not be initiated until at least 25 cm of new growth has accumulated above last year's stubble [21]. To ensure a successful seeding, it is recommended that one growing season be required for establishing tall wheatgrass on irrigated land and two growing seasons under dryland conditions. The major limitation in establishing tall wheatgrass stands are that young seedlings are slow to establish. Due to its late maturity, competitive ability, and tendency to become coarse during the growing season, it is recommended that tall wheatgrass be seeded alone rather than in a mixture with other grasses [66]. Although it tends to become coarse at advanced stages of maturity, when managed properly, tall wheatgrass has relatively good palatability and nutritional value. It is usually recommended for cattle; however, it has proven to be a good source of grazing for sheep [98].

Based on Vogel and Moore [103], sufficient variation exists in NPGS collections, particularly, PIs 98526, 264770, 283163, and 401006 to improve biomass production through selection in tall wheatgrass. On saline soils that ranged from 1.7 to 21.7 mmhos under dryland conditions, tall wheatgrass (cv. Alkar) averaged 4,331 kg ha^{-1} over a three-year period compared to 4,405 kg ha^{-1} for intermediate wheatgrass (cv. Greenar) and 4,107 kg ha^{-1} for the RS hybrid (cv. NewHy) in NRCS plant materials salinity trials in Roosevelt, UT [104]. In an irrigated trial near Elmo, UT, on saline soils that ranged in EC values from 5.7 to 20, tall wheatgrass (cv. Alkar) averaged 3,319 kg ha^{-1} over a four-year period compared to 4,624 kg ha^{-1} for tall fescue (cv. Festorina) and 2,376 kg ha^{-1} for the RS hybrid (cv. NewHy) [104]. On an upland site near Hays, Kansas, tall wheatgrass cultivars Alkar and "Jose" averaged 5,600 and 4,26 kg ha^{-1} over 3 years, respectively, compared to 3,696 and 2,800 kg ha^{-1} in intermediate wheatgrass cultivars Oahe and Slate, respectively [105]. Alkar tall wheatgrass ranked among the four highest entries for overall biomass yield, averaging 22,800 kg ha^{-1} per year over five cuttings, in a comparison of 21 warm-season and six cool-season grasses [1].

Because of its tall stature and caespitose growth habit, tall wheatgrass provides excellent nesting and cover for upland game birds. Its seeds remain on the plant relatively well, providing feed for birds during periods of deep snow cover. The species has shown to have value in plantings as a barrier against wind and drifting snow [102].

Genetic Resources

Tall wheatgrass is genomically related to the intermediate wheatgrass complex. Intensive cytogenetic studies have established that it is essentially an autodecaploid, comprising five sets of genomes, designated $\mathbf{E^e}$ or $\mathbf{E^b}$ [106]. The $\mathbf{E^e}$ genome originated from the diploid *T. elongatum* and the $\mathbf{E^b}$ genome originated from *T. bessarabicum*. Tall wheatgrass has proven to be valuable in wide hybridization programs to transfer genes conditioning resistance to salinity, drought, and disease to wheat [35, 107]. Molecular genetic markers developed from *T. intermedium* ($\mathbf{E^eE^eE^bE^bStSt}$), *T. bessarabicum* ($\mathbf{E^bE^b}$), and *T. elongatum* ($\mathbf{E^eE^e}$) should also be useful for tall wheatgrass [84].

Breeding Strategies/and Traits

The gene base of tall wheatgrass included in North American breeding programs is relatively narrow, with most cultivars tracing to one or two plant introductions. "Largo" the first cultivar to be released was derived from PI 109452, an accession collected by the Westover-Enlow expedition in Turkey. It was originally increased at the USDA-SCS nursery at Albuquerque, New Mexico, and the Utah Agricultural Experiment Station at Logan, Utah, cooperatively with USDA-ARS and released in 1937 [91].

Alkar, which is the widest used cultivar, was selected at the USDA-SCS Plant Materials Center at Pullman, Washington, and released in 1951 [91]. Its parental germplasm was derived from PI 98526, an accession obtained from the USSR via the N. I. Vavilov Institute of Plant Industry in 1932. Alkar is widely used in the Pacific Northwest and the Intermountain Region for pastures in wet, alkaline conditions [102, 108].

The cultivar "Jose" was released in 1965 and has been used for pasture and hay in irrigated areas of New Mexico and Colorado at elevations up to 2,300 m, as well as on range sites where alkali and salinity prohibit the use of other productive grasses. It is reported to be more acceptable to grazing animals than cultivars such as Alkar and Largo [109].

"Orbit" is the first cultivar of tall wheatgrass to be licensed for sale in Canada and was released in 1966 by Agriculture Canada at Swift Current, Saskatchewan. It is a composite of nine open-pollinated lines and one three-clone synthetic that were derived from PI 98526 and locally selected strains. The breeding population benefited from natural selection for winter hardiness. It is also characterized by relatively good seed and forage yield.

"Tyrrell" was registered in 1981 by the Victorian Department of Agriculture, Australia. It was selected from Largo, and subsequent evaluation trials have established that it is distinctly different from Largo. Its main assets are high salt tolerance and ability to grow and persist on highly alkaline soil sand salt seepage areas. It is particularly well adapted to salt-affected land typical of northwestern Victoria in Australia [110].

The cultivar "Platte" was released by the USDA-ARS and Nebraska Agricultural Experiment Station. Its parentage consists of selections from Nebraska 98526 and another breeding line. The cultivar is noted for its winter hardiness and improved forage and seed production. It is particularly well adapted to alkaline sites in lower valleys of Platte River drainage [111].

Seed Production

Tall wheatgrass grown for seed production should be planted in 71–91-cm rows and cultivated or 30–36-cm rows uncultivated. It typically produces 336 kg ha^{-1} under dryland conditions and 672 kg ha^{-1} under irrigated conditions [97].

Market Development and Macroeconomic Considerations

At this writing, cool-season biomass grasses are not cost-competitive with other biomass feedstocks or other Mountain West energy sources like natural gas. The agronomic cost analysis presented in this chapter provides a step towards cultivating the market for cool-season biomass grasses. With a better understanding of agronomic costs, the biomass industry may eventually become cost-competitive with other energy sources, especially when environmental benefits are calculated. A biomass market in the Mountain West could also contribute to regional economic prosperity if the market diversifies the region's energy portfolio. The first part of this chapter provides a review of macroeconomic, supply chain, and policy considerations that could be used to establish markets and policies for cool-season biomass grasses. This is followed by an agronomic cost analysis and discussion about barriers to commercialization.

Stable, low energy prices are directly linked to economic prosperity. Sharp commodity price increases, like abrupt energy price increases, can create an economic domino effect. For example, disruptions in crude oil supplies result in rising diesel prices. This subsequently increases transportation and agricultural production costs, eventually leading to inflation. Policymakers take considerable measures to diversify energy sources for transportation, electricity generation, and aviation so that energy costs remain stable. Adequate diversification and domestic production of fuel sources is defined by many policymakers as "energy security" [112]. An energy portfolio diversified with biomass-based energy could improve the Mountain West's energy security. Policies that encourage market development, energy diversification, and energy security could jump-start the market for cool-season biomass grasses, although long-term market viability hinges upon whether crops can be produced at competitive costs.

Ideally, profitability calculations should include net environmental costs. Laws and regulations require policymakers to balance energy security with environmental targets that consider greenhouse gas emissions, soil reclamation and remediation, and nutrient management. As established earlier in the chapter, cool-season biomass grasses may provide several of these environmental benefits. If a full environmental cost accounting of environmental impacts is conducted, then biomass-based energy cost-competitiveness may improve. Energy security and environmental policy goals provide both opportunities and challenges for biofuel production in the Mountain West.

On a national level, biofuels have been promoted as a means for increasing domestic energy production while meeting environmental regulations, although the effectiveness to which biofuels fulfill these objectives is continually under discussion. As previously stated, EISA and the RFS policies have attempted to increase domestic biofuel energy production. These policies are linked with considerable US biodiesel production increases from 87 million L in 2004 to 3,107 million L in 2011. The RFS calls for 136 billion L of biofuels to be created annually by the year 2020.

Based on current examples, biofuel policies have arguably been successful in establishing markets for US biofuels. Recent studies demonstrate that biofuel production is a commercially viable enterprise in some regions of the USA. For example, in the Midwest, there is sufficient supply and demand for corn ethanol, and the market in this region is now considered economically viable. At this writing the corn ethanol market can function without the support of many US subsidies [113]. Results from life cycle analysis that evaluate environmental impacts from "cradle to grave" note varying degrees of environmental benefits. There are notable concerns as to whether biofuel feedstocks displace food and whether US biofuel policies could contribute to higher domestic and international agricultural prices along with food prices. Some authors have demonstrated a strong correlation between biofuel production and rising global food prices, although other economists have noted that periods of high global food prices have resulted from a complex set of issues and that only select US biofuel policies have a minimal effect on food prices [114]. This debate will likely continue into the future as additional data become available. Nevertheless, what is relevant is that biofuel crops produced in the Mountain West states should be produced at low-input costs and ideally should not compete with crops intended for established uses such as food and feed.

If biofuel production can be established in an economically feasible way in the Mountain West, then this may be a market-based, environmentally desirable solution to energy security.

Recent studies show that the farm costs of producing switchgrass for cellulosic biofuel are estimated to be $40–60 per metric ton. A key component to profitable biomass production is maintaining consistently low-input costs [115]. A central criterion for the production of biomass crops are high yields with low production costs. The high price of production is driven, in part, by the high cost of inputs, such as water, as well as high transportation costs [4, 5]. The requirement of a low-cost delivered feedstock may be challenging to producers.

In theory, perennial grasses could be a desirable source for biofuel production because they can be grown on marginal lands with low water and fertilizer requirements and do not otherwise compete with other food/feed crops. Preliminary data suggest that perennial grasses could also improve soil carbon and nitrogen balances, indicating that this could be an environmentally desirable source of energy biofeedstock. The challenge is producing grasses in sufficient quantities to establish a regional market. Agronomic and biorefining costs must be low enough so that the prices are competitive with energy sources such as natural gas. Likewise, prices must be high enough so that agricultural producers will be willing and able to supply a consistent amount of biofuel feedstocks for profitable biorefinery production and to consistently fulfill fuel delivery contracts, ensuring that there are no fuel shortages. In other words, perennial grass biofeedstocks must be cost-competitive and reliably available to maintain stable consumer fuel prices while providing the supply chain with enough incentive to reliably produce the biofuel feedstock.

Identifying the incentives for producers in the Mountain West to grow biomass for biofuel is likely to be challenging. Biorefinery owners need a known, available, and constant supply of biomass to maintain an uninterrupted operation of their biorefinery, and it would seem appropriate for them to secure multiyear contracts with biomass producers. Will producers be willing to enter into multiyear contracts that will set contract conditions over multiyears? If biorefinery owners choose to lease fields from producers and produce their own biomass, will land owners be willing to enter into multiyear leases that result in their land being committed to a single production system over a long period of time? If these two options are not feasible, can biorefineries capitalize themselves sufficiently and secure the needed human resources and expertise to create the entire supply chain and own and operate a large enough land area to produce sufficient biomass to operate their biorefinery?

Not surprisingly, many steps along the supply chain must be cultivated for perennial grasses to be a viable source of bioenergy feedstock. Calculating and improving agricultural production costs at the farm level is a good way to begin supply chain development. Fore et al. [115], for example, calculated niche biofuel and feedstock costs for small, on-farm production. In their example, they find that neither soybeans nor canola was cost-competitive with petroleum diesel when feedstocks were valued at market price, but that under certain scenarios, the economic feasibility of straight-vegetable-oil (SVO)-based fuels and diesel could be similar. In a Colorado-specific example, the economic feasibility of growing the oilseed crop *Camelina sativa* ("camelina") in the Mountain West was modeled to produce value-added protein feed supplement, SVO-based biofuel, and farm energy independence [116]. Results from stochastic crop rotation budget showed that producers have a 50 % likelihood of breaking even when diesel prices reach $\$1.14\ L^{-1}$, although an experienced producer could achieve profitability 90 % of the time (using expected values of input prices) when diesel is at $\$0.81\ L^{-1}$.

Using a specific location as a test case allows an agronomic-economic model to be populated with examples, so that variables can be isolated and replicated elsewhere. This approach is supported by the literature, as others have noted that feedstocks must be tailored to be region specific in order to feasibly grow biofuels throughout the USA [117]. In other words, if economic profitability can be achieved at the farm level for niche biofuel markets, like those presented above, others may be encouraged to replicate the results. This momentum may lead to improvements in cost-efficiency and expanded production of perennial grasses as bioenergy feedstocks in the Mountain West. Ensuring the availability of a consistent number of producers/suppliers is a positive step towards attracting investment in a regional biorefinery and establishing a supply chain. Some people argue that the production of grass species will provide growers with dual market opportunities. Farmers can sell harvested grasses into traditional feed markets, and when prices are favorable, they can sell harvested grasses into the biomass/biofuel market. This approach does not provide for a reliable supply chain to meet the needs of a biorefinery.

Economic Feasibility of Perennial Grass Production in Western Colorado

Using the case study approach, this section presents an agronomic-economic model and a crop enterprise budgeting tool for growing perennial grasses in the Mountain West, with the intention that the model can eventually be replicated elsewhere and a regional market for perennial grasses can develop.

The cost of producing biofuel feedstocks is a major hurdle for growers [118], as production has been on too small of a scale to ensure consistent profitability [119]. One key component to profitable commodity production is maintaining consistently low-input costs [115]. Agronomic-economic data were collected to develop a crop enterprise budget tool [120] for herbaceous plant species in western Colorado. Field performances of four herbaceous biomass entries (factor 1) and four fertility input levels (factor 2) are currently being evaluated to assess their effect on biomass production over a long-term testing period at three locations in western Colorado. A more elaborate description of the agronomic parameters is outlined in Pearson et al. [121].

The objective of the budget tool was to model the impact of agronomic changes on production costs. The enterprise budgeting tool was developed in an Excel spreadsheet that is user-friendly for a variety of audiences, including producers, crop consultants, extension agents, and others. Parameters can be adjusted to reflect variations in location, crop management, best/worst case scenarios, or optimizing a specific input. For the purposes of this paper, the parameters of the crop enterprise budget have been adjusted to reflect specific agronomic scenarios. Naturally, these scenarios, and the corresponding results, can vary according to the agronomic model.

As demonstrated in the crop enterprise budget scenarios presented in Table 6.2, of the four species, the introduced grass species demonstrates the lowest per hectare break-even price ($51.59) when grown using efficient agronomic management. In contrast, the native grass mix demonstrates a relatively lower yield and a substantially higher break-even price, at $315.35 per hectare, even with efficient agronomic practices. Increases in two key costs, diesel fuel, and irrigation water, not unexpectedly, directly affect production costs. Regardless of the scenario, producers with capital equipment constraints (e.g., no disking) incur approximately 20 % higher break-even prices due to reduced yields. The crop enterprise budget tool quantitatively shows how changing different input parameters affects potential profitability.

As additional agronomic data becomes available, comparisons can be made about the expected break-even costs in the years following crop establishment. At the moment, it appears that establishment costs for the native grass mix and switchgrass are higher than the introduced grass mix, because yields are not as high during the first 2 years of production. Preliminary data from Pearson et al. [121] demonstrates considerable increases in switchgrass yields in its third year of production. Thus, while there could be a higher opportunity cost at least

Table 6.2 Enterprise budget scenarios for biomass species trials in Fruita, Colorado

	Switchgrass	Tall fescue	Introduced mix	Native mix
Biomass production costs	Assumes 2 cuttings with the average yield per species, per cut, expressed in tons/acre for average of 2011 and 2012 (early establishment years' yields)			
Efficient management				
Cost per acre	$182.70	$152.10	$154.78	$157.67
Break-even price per acre	$121.80	$152.10	$51.59	$315.35
Inefficient management				
Cost per acre	$229.97	$191.72	$195.08	$198.69
Break-even price per acre	$153.31	$191.72	$65.03	$397.38

[a]Inefficient management is defined as a scenario in which the agricultural production is the capital equipment constrained so that production is conducted at 80 % of the efficiency of an optimal producer. The following input parameters were assumed for both management scenarios: $30/acre cost for deficit irrigation in a typical non-drought year, $10/h labor costs, 3 % operating loan, $4.00/gallon diesel fuel prices, and two cuttings. Yields of 1.5, 1.0, 3.0, and 0.5 t/acre, respectively, were used for switchgrass, tall fescue, and introduced and native species. These reflected the approximate 2-year average yields for early establishment years at the Fruita site (2011 and 2012)

initially for switchgrass, production costs could decrease if yields increase considerably in nonestablishment years. At this writing, switchgrass and the introduced grass mix could show promise as economically feasible crops on marginal lands.

In summary, this crop rotation budget exercise should be viewed in context as a first step towards isolating the agronomic and economic variables that influence the profitability of agronomic perennial grass biomass production targeted for the Mountain West. Additional field trial data will provide necessary information to agricultural producers who must decide whether or not to grow the crop. The crop budget and profitability estimates are steps in building a perennial grass market that could ultimately lead to a critical mass of agricultural producers who are willing and able to cultivate a crop that can be used as a biofuel in the arid Mountain West.

Barriers to Commercialization

At present, there are several supply chain barriers to commercialization. Agronomic production of perennial grasses has only been at the pilot scale. Before investing in commercial scale development, biorefineries must ensure that there will be both adequate biomass supply and demand for the finished product. Ultimately, biofuels must be reliably available and offered at a price point that competes with other fuel sources. However, investment in the biofuel supply chain could help overcome production and cost barriers and improve the overall economic structure of remote, agriculturally based Mountain West communities.

Developing a locally grown biofuel product could provide economic diversification to rural communities in the Mountain West. Establishing a regional supply chain for biofuel production could diversify fuel sources, thereby providing a degree of energy security against price increases or shortages. With strategic biorefinery locations, transportation costs could be minimized, so that the biofuel products could be competitively priced. If the perennial grasses are grown on marginal lands, it could provide agricultural producers a diversified agricultural product mix and an additional revenue stream from land that may not otherwise be in production.

The identification of sufficient land area within a cost-effective distance to support year-round operation of a biorefinery is a significant barrier to commercialization in many areas of the country including the Mountain West. The production of ethanol that uses corn for conversion has been economically feasible to locate biorefineries close to by-product users rather than only near the resource production sites. Corn grain can be railed across state lines to ethanol conversion facilities locations where by-products from a biorefinery are sold to cattle feeders.

Biomass from perennial grasses must be grown on land that does not compete with land that is currently being used for food/feed production. A variety of potential types of land that could be used for biomass production are marginal land, abandoned land, degraded land, idle land, underutilized land, wasteland, reclaimed land, and inefficient land. Identifying and quantifying such land that is suitable and available for biomass production is challenging. Determining the production and production stability potential of these lands for biomass production to meet the demands of a particular biorefinery is equally challenging.

As previously discussed, in order to establish the agricultural production segment of the supply chain, the perennial grass field trials should be replicated at multiple sites. Great care should be taken to measure cost, input, and yield data to ensure that agricultural producers set proper expectations for field performance. Cost and yield trends will help growers estimate feedstock quantity and contract price parameters for biorefinery contracts, and a critical mass of agricultural producers will be necessary in order to attract capital investment for a biorefinery.

Likewise, biorefineries will need to ramp up production levels to a point where they are able to provide predictable quantities of biofuel to fulfill fuel contracts and to ensure that there are no fuel supply disruptions. As previously noted, in order to establish a commercially viable market, it is important to control production costs, from growing and biorefining the feedstock, so that per gallon biofuel price is competitive with other commercially available fuels. It is also expected that the agricultural producers and biorefinery will earn a reasonable rate of return on their production – otherwise, there would not be an incentive for them to continue the biofuel supply chain. A fuel supply contract, possibly for a city or county service vehicle fleet, could provide assurance to producers that there will be a demand for the products that they produce. In small, rural economies like those in the Mountain West, there is a potential for the regionally grown, processed, and supply chain to develop and provide a cost-competitive product.

From a practical perspective, recent technological advances have improved the economic feasibility for developing non-conventional natural gas plays (defined as shale gas, coal bed methane, and tight gas sands) that can yield reliable natural gas production with high immediate payback on investment and competitive consumer prices. Many of these natural gas resources are located in the rural Mountain West communities that have been the subject of this chapter. Hence, natural gas development, rather than biofuel development, may actually serve as the low-cost energy resource that drives economic development in these regions. On the downside, while the benefit of low energy prices have been well established, unlike agricultural-based economies that create diversified economic sectors, oil and natural gas development leads to notoriously undiversified regional economies often leading to boom and bust economic cycles [122, 123]. While the USA is projected to be a net energy exporter during the next 30 years, this enthusiasm should be put in perspective with the perceived natural gas shortage from just a decade earlier. There is considerable economic benefit projected for natural gas development in the Mountain West; diversification of energy resources should always be an important goal to manage risk and to facilitate energy security.

At the present time, Mountain West communities are poised to benefit from the anticipated boom in natural gas production that is projected to displace coal as an electricity generation resource and eventually displace gasoline and diesel as a source for heavy fleet vehicles. There is little disagreement that natural gas reduces net greenhouse gas emissions compared to coal-based electricity generation

[124–126], although there are concerns about fugitive methane emissions, in part due to shale disturbance. Despite technological advances and improvements in environmental assessment and accountability for hydraulic fracturing, there is much to be learned about the non-conventional natural gas development process and accompanying environmental impacts. As recent, controversial, community meetings have shown decisions as to whether or not to proceed with natural gas development should be made on a community-specific basis with an attempt to include multiple stakeholders. Agriculturally based communities could make an informed decision about the mix of locally based energy production that best suits their community values, and this mix will likely address locally produced natural gas.

Another plausible scenario is that biomass could be coproduced on lands that primarily serve to meet soil protection and wildlife conservation goals [127]. Herbaceous perennial grasses provide benefits for land cover that improves soil and water protection, nutrient management, and wildlife habitat. The marginal lands that qualify for agricultural policies like the Conservation Reserve Program could serve dual policy goals of providing wildlife habitat and biomass production to establish a supply chain to sustain a regional economy. Considerable agronomic and economic work is necessary to make this economically desirable proposition for biomass supply chain in the Mountain West a sustainable reality.

Opportunities

For biomass production in the Mountain West, a goal of 6.7 dry ton ha^{-1} and a biofuel yield of 330 L ton^{-1} of biomass would produce 2,211 L ha^{-1} of biofuel. Compared to much of the rest of the country, the Mountain West has a large acreage of idle cropland, has a majority of the land in grassland pasture and range, and has one of the highest rates of crop failure. Using sustainable cropping practices for biomass production, well-adapted, dedicated perennial biomass crops would reduce the incidence of crop failure [128]. If 4 million hectares of the 142 million hectares of cropland, grassland, pasture, and range could be used for biomass, this land has the potential to produce 9.1 billion liters of biofuel annually, thus creating a significant economic opportunity. Production of this quantity of biobutanol in the Mountain West would make a significant contribution towards meeting the US Energy Independence and Security Act of 2007. The realization of these targets in the Mountain West will not happen in the short term. Certainly, such a successful enterprise in the Mountain West would create new business and thousands of new jobs.

Biofuel crops may require a small amount of supplemental irrigation to ensure their economic viability [129]. Nevertheless, some dedicated herbaceous energy crop species, such as native and naturalized grasses, may have higher water-use efficiencies and be more heat and drought tolerant than annual row crops. Furthermore, in some cases, the use of municipal, industrial, or gray water may be available for irrigating biofuel crops and would not compete with freshwater sources.

Production of perennial grasses for biomass would create opportunities that are environmentally beneficial. Dedicated biofuel crops are not likely to have adverse impacts on water quality because the use of pesticides and fertilizers is limited. It is possible that the production of dedicated biofuel crops could actually improve water quality under the proper crop management production system. For example, in western Colorado, the production of low-input biomass would reduce irrigation applications and thus reduce salt and selenium loading into the Colorado River and could improve water quality for downstream users in California and other western states.

Because of their deep systems and year-round cover, herbaceous perennial energy crops have the potential to reduce soil erosion rates, sequester and enhance soil organic carbon, and increase soil fertility over time compared to annual corn grain production. For example, soil erosion when growing switchgrass was approximately 30 times lower during the first year, and in the second and third years, soil erosion was 600 times lower compared to soil erosion that typically occurs in annual crops [130].

Conclusion

Herbaceous perennial grasses as lignocellulosic resources are a preferred feedstock source for biofuels because they have a neutral carbon budget, require few agronomic inputs, can be readily managed to be environmentally friendly, and have the potential to be grown on a variety of lands, soils, and crop production situations. Large regions of the Mountain West are dominated by cool-season grasses. These cool-season perennial grasses could be a desirable source for biofuel production because they can be grown on marginal lands with low water and fertilizer requirements and on such land that does not otherwise compete with food/feed crops. Basin wildrye, basin x creeping wildrye hybrids, intermediate wheatgrass, and tall wheatgrass are considered to be viable candidates for lignocellulosic biomass production.

Agronomic production of perennial grasses for biomass to date has largely been at the pilot scale in many areas of the country. Crops and cropping systems needed to produce low-input herbaceous perennial crops to support a bioenergy economy in the Mountain West are essentially unknown. Identifying sufficient land area within cost-effective distances to support year-round operation of a biorefinery is a significant barrier to commercialization in many areas of the country including the Mountain West. A variety of potential types of land that could be used for biomass production are possible, but identifying and quantifying such land that is suitable and available for biomass production will be challenging.

Stable energy prices are a critical component for maintaining a stable macroeconomy, which presents both challenges and opportunities for developing new energy sources. A viable market requires both product demand and a reliable supply chain. Steps towards achieving this goal include quantifying biomass production costs and developing approaches to improve these agronomic costs.

Policymakers should consider instituting policies that encourage supply side contracts for locally produced energy sources, in order to encourage local economic development and to diversify energy resources. Policies are already in place that target biofuel production, which provides a critical link between agriculture and energy. Agricultural production is the economic and cultural lifeblood of many western rural communities [131]. In the event of a fuel supply disruption, it would be important to these rural communities and the agricultural supply chain to ensure that agricultural production continues. It is once again essential to emphasize that successful integration of perennial grasses would only eliminate a small fraction of the need for energy sources. Small fractions can quickly add up to significant sums if other biofuels options are implemented elsewhere.

Developing a locally grown biomass and biofuel products could provide economic diversification to rural communities in the Mountain West. Establishing a regional supply chain for biofuel production could diversify fuel sources, thereby providing a degree of energy security against price increases or shortages. The commercial production of cool-season perennial grass species as found in basin wildrye, basin x creeping wildrye hybrids, intermediate wheatgrass, and tall wheatgrass for lignocellulosic biomass production in the Mountain West will require considerable genetic improvement to develop these plant species for suitable biomass production. Since the 1990s, there has been a constant decline in range grass breeding programs in the USA due to reduced budgets and other program changes. Current range grass breeding programs have emphasized forage quality over yield in more recent intermediate wheatgrass cultivars as well as emphasis on developing plant materials that establish and are more persistent on dry, harsh disturbed rangelands capable of competing against invasive annual grasses, thus reducing the frequency and magnitude of wildfires and maintaining our natural resources. Numerous other aspects of the supply chain and conversion processes appropriate for the Mountain West will also require research and development efforts.

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