Cover Crop Biomass Production in Temperate Agroecozones

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ABSTRACT

Cover crop (CC) biomass production dictates agricultural and environmental services that CCs deliver, but finding a review on this topic is difficult. We synthesized published data on CC biomass production for 20 common CC species in temperate regions and discussed factors affecting CC biomass production. Review of 389 papers indicated CC biomass production was 3.37 ± 2.96 Mg ha^{-1} (mean ± SD). Cover crop biomass production for the top five biomass-producing species was: sorghum (*Sorghum* sp.) (5.99 Mg ha^{-1}) > sunn hemp (*Crotalaria juncea* L.) (5.77 Mg ha^{-1}) > millet (*Pennisetum glaucum* L.) (4.95 Mg ha^{-1}) > rye (*Secale cereale* L.) (4.93 Mg ha^{-1}) > two-species mix (4.18 Mg ha^{-1}). In humid regions (>750 mm precipitation), CC biomass production ranged from 1.67 to 6.30 Mg ha^{-1} depending on species. In regions with <750 mm precipitation, CC biomass production ranged from 0.87 to 6.03 Mg ha^{-1}. Cover crop biomass production was in this order by cropping system: vegetables > other systems [soybean (*Glycine max* L.), cotton (*Gossypium hirsutum* L.), and others] > maize (*Zea mays* L.) > small grains. Rye was among the most common and highest biomass producing species in most regions and cropping systems. Drill-planting and maximizing CC growing season, such as early planting or late termination, can increase CC biomass production. Irrigation at establishment increased CC biomass production for legumes and mixes in humid regions, and all CC groups in semiarid regions. Overall, CCs can produce significant amount of biomass, but this can be highly dependent on climate, CC species, cropping system, and management.

Core Ideas

- Cover crop (CC) biomass production across temperate regions averaged 3.37 ± 2.96 Mg ha^{-1}.
- Ten high-biomass producing CCs in temperate ecoregions were in this order: sorghum > sunn hemp > millet > rye > mixes > crimson clover > barley = hairy vetch > annual ryegrass > oat.
- Cover crop biomass production was greater in humid than semiarid regions and in areas with relatively high mean temperatures.
- Cover crop biomass production by cropping system was in this order: vegetables > other systems > maize > small grains.
- Cover crop biomass production generally increased with drill-planting and increased seeding rate and growing season.

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Interest in using cover crops (CCs) to improve agricultural sustainability has increased in recent decades. For example, CCs are considered a leading strategy to improve soil properties (Blanco-Canqui et al., 2015). However, literature suggests that effects of CCs on soil properties and crop yields can be highly variable, particularly in the short-term (Blanco-Canqui et al., 2015; Poeplau and Don, 2015; Vukicevich et al., 2016; Finney et al., 2017; Ruis and Blanco-Canqui, 2017). One key factor that appears to dictate CC effects on soil and crop production is the amount of CC biomass produced. While many reviewed CC effects on soil properties (Blanco-Canqui et al., 2015), C sequestration (Poeplau and Don, 2015; Ruis and Blanco-Canqui, 2017), soil biology (Vukicevich et al., 2016; Finney et al., 2017), and other topics, an overall synthesis of CC biomass production under different cropping systems, management systems, CC species, and climatic conditions across temperate regions worldwide is not available. Individual studies suggest that CC biomass production can be highly variable, even within the same region (Finney et al., 2016; Thomas et al., 2016, 2017).

Several studies recently discussed the multifunctionality of CCs including their uses for biofuel, haying, and grazing (Blanco-Canqui et al., 2015; Holman et al., 2018). Such potential additional benefits of CCs require a better understanding of CC biomass production in different regions and management scenarios. Individual studies on CC biomass production are abundant particularly in temperate regions, but synthesis and discussion of CC biomass production and production drivers are lacking.

Some key recurring questions include: (i) What CC species or groups produce the largest amount of biomass within a region? (ii) Which are the best performing CCs for a given area? and: (iii) What factors affect CC biomass production in different regions? This review addresses the above questions through a comprehensive search and detailed summary. Our objectives were to (i) synthesize data on CC biomass production for the 20 most common CC species in temperate regions and (ii) discuss factors affecting such production.

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Abbreviations: CC, cover crop.

APPROACH

We reviewed papers from temperate regions that included the 20 most common CC species (SARE, 2017). These species were rye, oats (*Avena sativa* L.), winter wheat (*Triticum aestivum* L.), annual ryegrass (*Lolium multiflorum* L.), triticale (×*Tritiosecale*), winter barley (*Hordeum vulgare* L.), radish (*Raphanus sativus* L.), rapeseed (*Brassica napus* L.), turnip (*Brassica rapa* L.), canola (*Brassica juncea* L.), crimson clover (*Trifolium incarnatum* L.), winter pea (*Pisum sativum* L.), hairy vetch (*Vicia villosa* L.), cowpea (*Vigna unguiculata* L.), red clover (*Trifolium pratense* L.), sunn hemp, buckwheat (*Fagopyrum esculentum* L.), sorghum-sudangrass, and millet. We included sorghum or sudangrass and multiple species of millet.

We reviewed literature using Web of Science (www.webofknowledge.com) with no set date range. The search terms included "cover crops" and "biomass" (675 papers), "cover crops" and "dry matter" (<200 papers), and "cover crops" and "residue" (<200 papers), among others. Finally, we searched by "cover crops" and each of the 20 most common CC species. We did not include papers based on greenhouse or pot studies as our goal was to assess CC biomass production under field conditions. We also did not include studies conducted in orchards and other perennial crops as our goal was to focus on annual cropping systems. In all, we tabulated 389 papers from temperate regions, with over 2600 observations. We also discussed CC mixes, if present within the 389 papers.

For discussion purposes, we counted observations rather than papers because many papers evaluated CC biomass production from multiple CC species and sites within the same paper. If a paper reported multiple years of data, we computed a mean across all years. Thus, each treatment or CC species contributed an observation from a paper. If data were from multiple sites, each site contributed an observation unless the paper reported data across all sites. To better explore how some factors, such as climate and CC species or groups affect CC biomass production, we classified CC data reports by climatic region and by functional group, as described below.

In our review, we classified study sites reporting CC biomass production into climatic regions by precipitation. The climatic regions were humid temperate and semiarid temperate (Unger and Vigil, 1998). Based on this classification, humid regions received >750 mm annual precipitation and semiarid regions received <750 mm annual precipitation. The humid and semiarid regions were further classified by temperature into warm, mild, and cold zones based on USDA plant hardiness zones (>zone 7 = warm, zone 5 to 7 = mild, <zone 5 = cold) because growing season duration and temperatures increase from north to south (USDA, 2012). For European countries, we based temperature zone classification on mean annual temperature. For studies from the United States that did not report mean annual temperature or precipitation, we estimated the climatic information using the site usclimatedata.com for the city provided in the studies. If the city was not present in the list at usclimatedata.com, then we used data from the nearest city on the list. Note that, in some cases, temperature or precipitation information was unavailable.

To differentiate CC biomass production by different CC species, we classified CCs into these groups when necessary: grasses, brassicas, legumes, mixes, and miscellaneous species. The last category included the CC buckwheat. We classified mixes by two-species mix, which contained only two species or complex mix which contained >2 species. We computed means and standard deviations by precipitation, temperature, CC groups, cropping system, fertilization, irrigation, planting and termination date, and their combinations. Below, we discuss how climatic region affects CC biomass production and how CC groups and cropping system influenced CC biomass production within each region. We discuss CC species and cropping systems under their respective climates because their performance can vary with climatic conditions.

GLOBAL COVER CROP BIOMASS PRODUCTION

The number of observations on CC biomass production by continent was in this order: North America > Europe > Asia. Across all studies, mean CC biomass production was 3.37 ± 2.96 Mg ha^{-1}. Cover crop biomass production ranged from 0 to 32 Mg ha^{-1} yr^{-1} across locations, indicating production was highly variable. Across the region, CC biomass production for the top ten of the 20 most common CC species was in this order: sorghum (5.99 Mg ha^{-1}) > sunn hemp (5.77 Mg ha^{-1}) > millet (4.95 Mg ha^{-1}) > rye (4.93 Mg ha^{-1}) > two-species mix (4.18 Mg ha^{-1}) > crimson clover (3.53 Mg ha^{-1}) > barley (3.22 Mg ha^{-1}) = hairy vetch (3.22 Mg ha^{-1}) > annual ryegrass (3.02 Mg ha^{-1}) > oat (3.00 Mg ha^{-1}) > others (1.70 to 2.97 Mg ha^{-1}). The most commonly studied CCs were rye with nearly 450 observations; two-species mix with 325; hairy vetch with 257; radishes with 162; complex mix with 144; and red clover, oats, and crimson clover with about 136 observations each. Except for radishes, complex mix, and red clover, these most commonly studied species also had the highest biomass production. Biomass production was generally the lowest when CC growing season was relatively short in colder climates, such as in northern areas of North America. The high variability in CC biomass production can be attributed to site-specific factors including climate, cropping system, CC groups, planting date, seeding rate, growing season, planting method, irrigation, fertilization, and soil texture, among others (Fig. 1).

HUMID TEMPERATE REGIONS

The humid temperate region (>750 mm annual precipitation) included 1715 observations, mostly from North America and Europe, and represented about 64% of total observations. Mean CC biomass production was 3.78 ± 3.08 Mg ha^{-1}. This indicates that CC biomass production in this region can be highly variable, apparently due to differences among CC species and other factors. Figure 2 shows the effects of temperature and precipitation on CC biomass production. In general, in the humid region, CC biomass production increased from cold to mild to warm temperature zones. Based on this observation, we discuss CC biomass production by CC species and temperature zones.

Cover Crop Species

Cover crop species could be an important factor that determines biomass production within a climatic region due to differences in CC physiology and suitability of different plants to certain environments. In this region (Fig. 3), CC biomass production by species was in this order: sorghum > sunn hemp

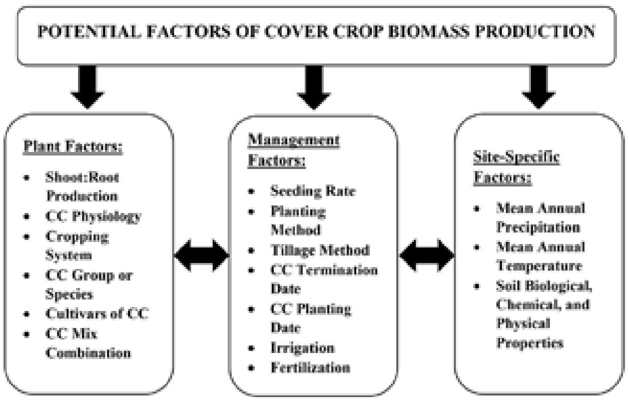

Fig. 1. Interrelated factors influencing cover crop (CC) biomass production.

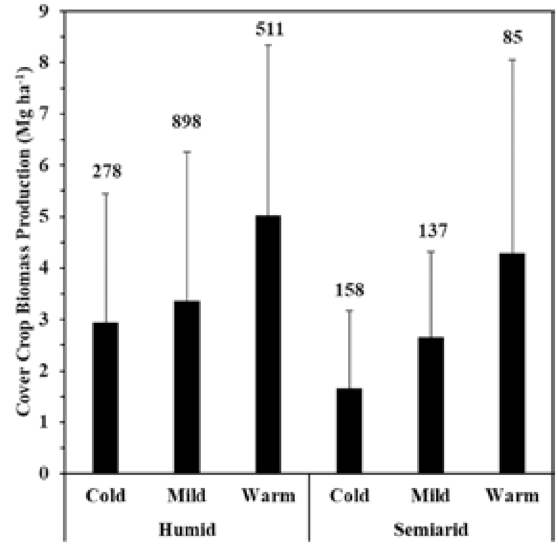

Fig. 2. Influence of climatic region on cover crop biomass production. Bars are standard deviation of the mean. Humid areas have mean annual precipitation >750 mm and semiarid <750 mm. Cold region was USDA hardiness zone <5; mild USDA hardiness zone 5 to 7; warm USDA hardiness zone >7.

> millet > rye > two-species mix > annual ryegrass > crimson clover > hairy vetch > complex mix > turnip > others. The most studied species were rye > two-species mix > hairy vetch > crimson clover > complex mix > wheat and sunn hemp > others, which generally coincides with the species that produced the most biomass. This suggests that in this region, rye, two-species mix, sunn hemp, hairy vetch, and crimson clover are the most common and the highest biomass producing species. As shown in Fig. 3, CC biomass production can vary significantly even within the same CC species; thus, we also explore CC biomass production by temperature zone.

Cold Zone of the Humid Region

In this zone, CC biomass production ranged from 1.1 to 5.1 Mg ha^{-1} across species as shown in Fig. 4. Cover crop biomass production was the highest for millet > complex mix > sorghum > turnip > rapeseed > two-species mix > radish > barley > triticale > pea > others. However, turnip and rapeseed CC biomass production was evaluated in very few instances. The most commonly evaluated species were (with at least 10 observations): triticale > rye > complex mix > hairy vetch > red clover > two-species mix > oat = radish. Thus, the species that were both the most studied and highest biomass producers were complex mix, triticale, rye, radish, and two-species mix ranging in biomass production from 2.9 to 5.0 Mg ha^{-1}. About 75% of the CC species

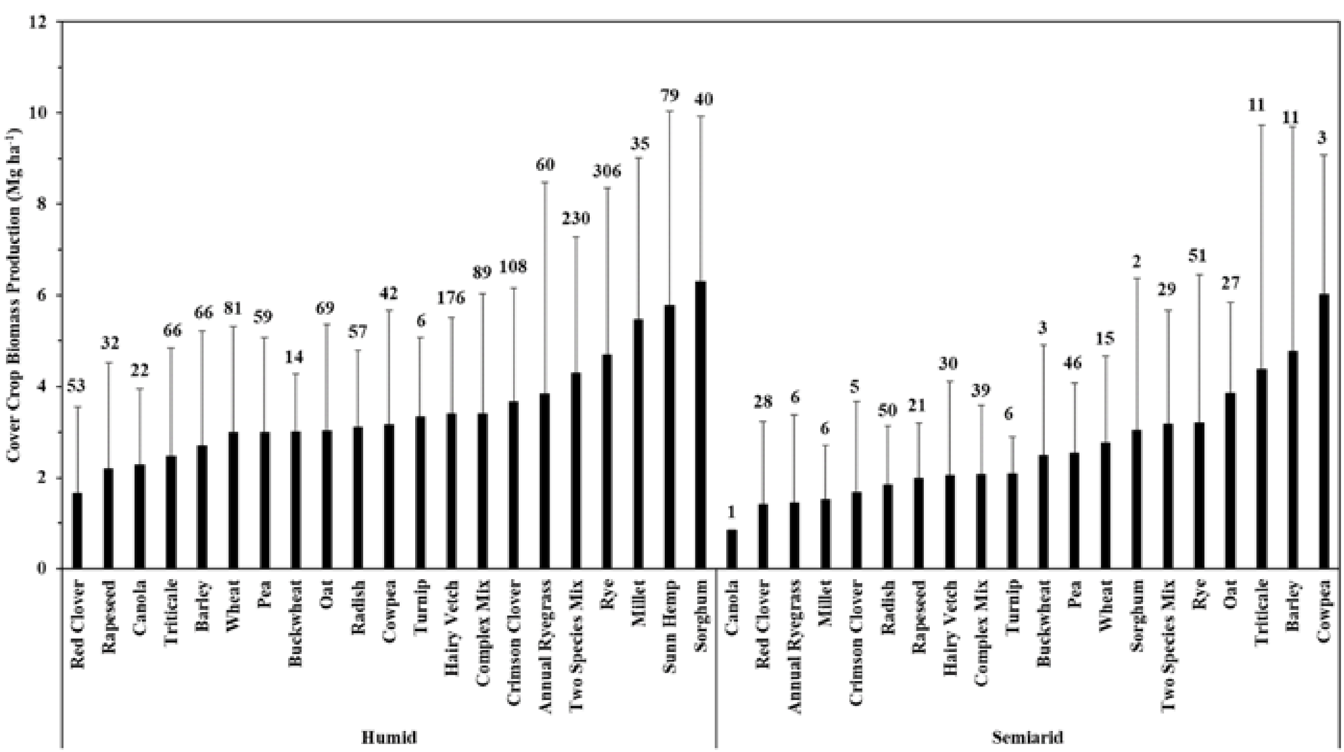

Fig. 3. Mean cover crop biomass production by cover crop species and climatic region. Bars are standard deviation of the mean. The humid region had mean annual precipitation >750 mm and semiarid <750 mm. The cold region was USDA hardiness zone <5; mild USDA hardiness zone 5 to 7; warm USDA hardiness zone >7.

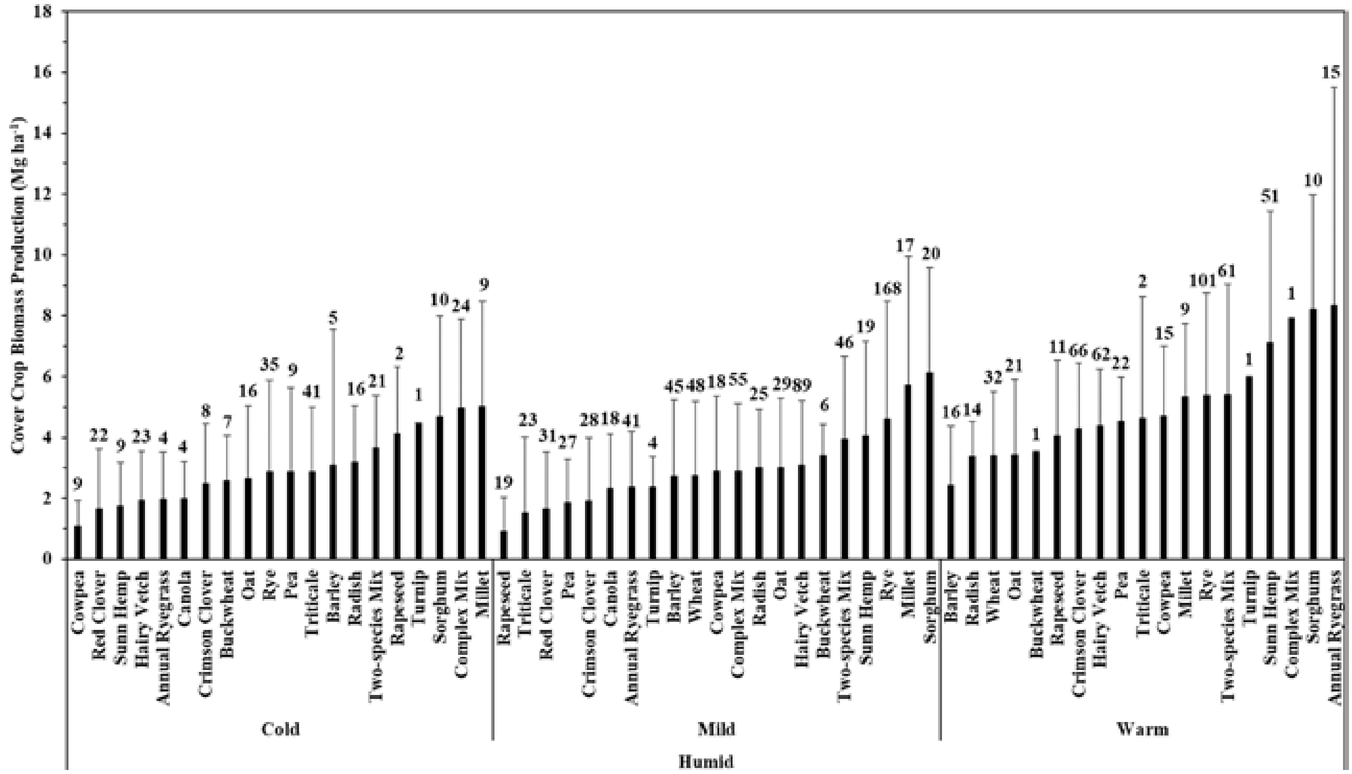

Fig. 4. Mean cover crop biomass production by cover crop species in the humid region (>750 mm precipitation) by temperature zone. Bars are standard deviation of the mean. Numbers above standard deviation bars are the number of observations. The cold region were USDA hardiness zone <5; mild USDA hardiness zone 5 to 7; warm USDA hardiness zone >7.

evaluated in the cold humid region produced at least 2 Mg ha^{-1} of biomass, 25% produced at least 4 Mg ha^{-1}, and no species produced more than 6 Mg ha^{-1}. Generally, species typically thought to thrive in cold conditions, such as radishes, were among those with the greatest biomass production.

Mild Zone of the Humid Region

In the mild zone, CC biomass production ranged from 0.9 to 6.3 Mg ha^{-1} (Fig. 4). Biomass production was in this order: sorghum > millet > rye > sunn hemp > two-species mix > buckwheat > hairy vetch > oat > radish > complex mix > others. Commonly evaluated species were: rye > hairy vetch > complex mix > wheat > two-species mix > barley > annual ryegrass. This indicates that rye, two-species mix, complex mix, and hairy vetch were the most common of the highest biomass producing species, which, except for rye and the two types of mixes, are different species from the cold zone. In this zone, rye produced nearly 60% more biomass than the cold zone (2.9 vs. 4.6 Mg ha^{-1}). Of the species evaluated in this region, about 76% produced biomass of at least 2 Mg ha^{-1}, about 19% produced at least 4 Mg ha^{-1} and only about 5% produced at least 6 Mg ha^{-1}. This suggests that more species produce higher quantities of biomass in the cold zone. In general, the highest biomass producing species in this zone are of two categories: those that thrive in warm conditions and those that thrive in cool conditions. Their use likely depends on cropping system, which will be discussed under “Cropping System”.

Warm Zone of the Humid Region

In this zone, CC biomass production ranged from 2.5 to 8.3 Mg ha^{-1} (Fig. 4). Biomass production was in this order: annual ryegrass > sorghum > complex mix > sunn hemp > turnip > two-species mix > rye > millet > cowpea > triticale > others. However, turnip (n = 1), complex mix (n = 1), and triticale (n = 2) contributed very few observations. The most commonly studied species were: rye > crimson clover > hairy vetch > two-species mix > sunn hemp > wheat > pea > oat > barley > annual ryegrass = cowpea. This indicates that rye, annual ryegrass, sunn hemp, two-species mix, and cowpea were both commonly used CCs and produced the most biomass in the warm zone of the humid region. The only species that were both common and high biomass producing in the mild and warm zones were rye and two-species mix. Both species were high biomass producers and common in all three temperature zones. In this zone, all CC species produced at least 2 Mg ha^{-1} on average, while 74% produced at least 4 Mg ha^{-1}, and 26% produced at least 6 Mg ha^{-1}, indicating that more species produced biomass of at least 4 Mg ha^{-1} compared to the mild zone. Further, all species produced more than 2 Mg ha^{-1} biomass, which is about 25% more species than both the mild and cold zones of the highest biomass producing species, includes several that are considered to thrive in warm conditions (i.e., sunn hemp, sorghum).

Summary for Humid Temperate Region

Cover crop biomass production increased as temperature increased across the humid region, with greater numbers of species achieving 4 and 6 Mg ha^{-1} of biomass in the mild and warm zones relative to the cold zone (Table 1). In the warm zone, most CC groups and species produced large amounts of biomass, but management is likely key (i.e., planting warm-season when warm, planting cool-season when cool). Thus, there is greater flexibility in CC species options in warmer climates within the humid region. Rye, one of the most common species in all three

Table 1. Summary of how factors can affect cover crop (CC) biomass production based on literature review of 389 papers. Other cropping systems include soybean, cotton, and other relatively low biomass producing crops. Humid areas have mean annual precipitation > 750 mm and semiarid < 750 mm. Cold zone was USDA hardiness zone < 5; mild zone was USDA hardiness zone 5 to 7; warm zone USDA hardiness zone > 7.

Factor	Sub-factor	Key finding for CC biomass production
CC species		Sorghum (5.99 Mg ha^{-1}) > sunn hemp > millet > rye > two-species mix > crimson clover > barley = hairy vetch > annual ryegrass > oat > others (1.70 to 2.97 Mg ha^{-1})
CC groups	Humid	Most common and highest biomass producing: · In cold zone: complex mixes, triticale, rye, radish, two-species mix · In mild zone: rye, two species mixes, complex mix, hairy vetch · In warm zone: rye, annual ryegrass, sunn hemp, two-species mix, cowpea · Rye was the most common and produced 2.9 Mg ha^{-1} in the cold zone and 5.42 Mg ha^{-1} in the warm zone
	Semiarid	Most common and highest biomass producing: · In cold zone: pea, radish, complex mix · In mild zone: oat, two-species mix, rye, pea, radish · In warm zone: rye, oat
Cropping system		Most common and highest biomass producing: · Maize: rye, two-species mixes, hairy vetch · Diversified systems: generally rye · Other systems: rye, two-species mixes, hairy vetch, oat · Small grains: rye, complex mixes ·Vegetables: rye, sorghum, millet
Planting method		CC biomass production was higher with drilling compared to broadcast seeding of CCs
Growing season duration		·The longer the growing season, the greater the CC biomass production · Fall planting with spring termination was most common and produced, on average, 4.0 Mg ha^{-1} of biomass · Summer CC planting produced 2.5 to 3.1 Mg ha^{-1}
Seeding rate		Cover crop biomass production generally increased as the seeding rate increased
Tillage		Tillage did not generally affect CC biomass production
Irrigation		Irrigation increased CC biomass production for legumes and mixes in humid region, and brassicas, grasses, legumes, and mixes in the semiarid region
Fertilization		Fertilization increased CC biomass production for brassicas, grasses, and mixes, but may reduce biomass production for legumes

zones, performed well across all three zones producing 2.9 Mg ha^{-1} in the cold zone, 4.6 Mg ha^{-1} in the mild zone, and 5.4 Mg ha^{-1} in the warm zone. While mixes were among the top biomass producing species, the mix was typically comprised of at least one high biomass producing species like rye.

SEMIARID TEMPERATE REGIONS

Semiarid temperate regions were classified as those with <750 mm of annual precipitation, and further subdivided by annual temperature based on USDA hardiness zones (>zone 7 = warm, zone 5 to 7 = mild, <zone 5 = cold). This region included 399 of the >2600 observations from areas such as the western Great Plains of North America and parts of Europe. Mean CC biomass production in semiarid temperate regions was 2.61 ± 2.42 Mg ha^{-1}. Figure 2 shows the influence of temperature within this region. Mean CC biomass production increased 2.57 times from cold to warm zones within the semiarid region. Because of this large difference in biomass production from cold to warm zones, CC biomass production within this region will be discussed by temperature zone below.

Cover Crop Species

Cover crop biomass production in the semiarid region ranged from 0.9 to 6.0 Mg ha^{-1}, depending on species (Fig. 3). Cover crop species with the highest biomass production were cowpea > barley > triticale > oat > rye > two-species mix > sorghum > wheat > pea > buckwheat > others as shown in Fig. 3. The most commonly studied species were rye > radish > pea > complex mix > hairy vetch > two-species mix > red clover > oat > rapeseed > wheat > others. This suggests that generally in this region, rye, both types of mixes, and wheat are among the top biomass producing and common species, which is similar to the humid region. In some locations within this climatic region, particularly those with mean annual precipitation <500 mm, farmers are concerned about water use by CCs. Indeed, in the western areas of the United States, such as the Central Great Plains, CCs may reduce main crop yields in some years, likely due to reduced soil water content (Unger and Vigil, 1998; Nielsen et al., 2015, 2016).

Cold Zone of the Semiarid Region

In the cold zone (USDA hardiness zone <5) of the semiarid region, CC biomass production ranged from 0.2 to 3.3 Mg ha^{-1} (Fig. 5). The highest biomass producing CCs were wheat > oat > pea > turnip > rye > millet > triticale > complex mix > radish > red clover > others. The most studied species were: pea > radish > red clover > complex mix > hairy vetch > two-species mix > others. Note that most species across the cold zone had <10 observations (158 total for zone). Pea, radish, and complex mix CCs were the most common and highest biomass producing species. The CC biomass production rankings suggest that species that are tolerant of cold (radish, turnip, pea) are some of the highest biomass producing species for the region. About 69% of species produced at least 1 Mg ha^{-1} biomass, 31% produced at least 2 Mg ha^{-1}, and no species produced more than 4 Mg ha^{-1}. Thus, it appears that in the cold zone of the semiarid region, CC biomass production is substantially lower than

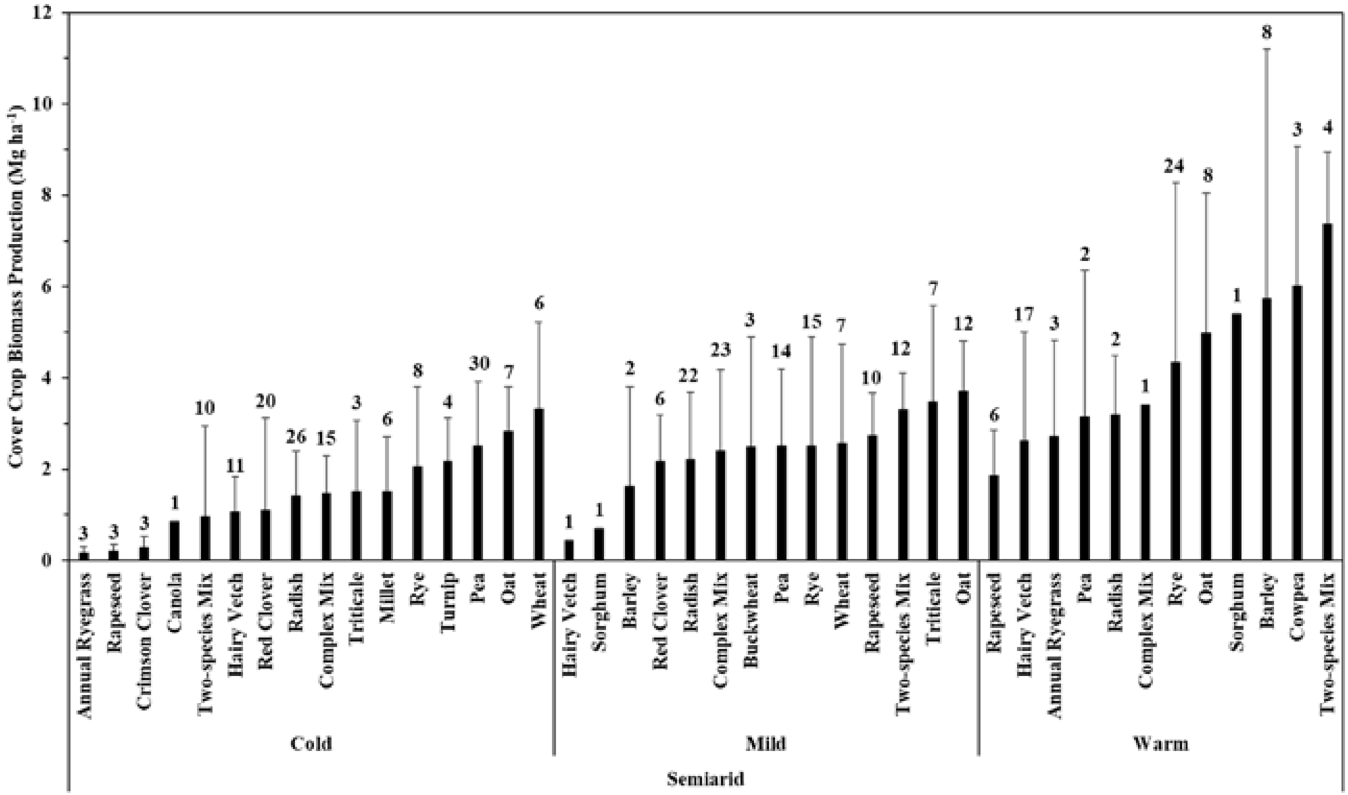

Fig. 5. Mean cover crop biomass production by cover crop species in the semiarid region (<750 mm precipitation) by temperature zone. Bars are standard deviation of the mean. Numbers above standard deviation bars are the number of observations. The cold region were USDA hardiness zone <5; mild USDA hardiness zone 5 to 7; warm USDA hardiness zone >7.

in the cold humid zone. Management, however, such as early planting or late termination, as discussed later, may be strategies to increase biomass production although this strategy could use more water intended for the next crop.

Mild Zone of the Semiarid Region

In the mild zone (USDA hardiness zone 5 to 7), CC biomass production ranged from 0.4 to 3.7 Mg ha^{-1} (Fig. 5). Cover crop biomass production was in this order: oat > triticale > two-species mix > rapeseed > wheat > rye > pea > buckwheat > complex mix > radish > others. The most common species were complex mix > radish > rye > pea > two-species mix = oat. Thus, the most common and highest biomass producing species were oat, two-species mix, rye, pea, and radish. These species are similar to those in the cold zone, except for two-species mix and rye. Pea CC produced the same amount of biomass in both zones while radish and oat produced about 0.85 Mg ha^{-1} more biomass in the mild zone compared to the cold zone. Biomass production was at least 1 Mg ha–1 for 86% of species and at least 2 Mg ha–1 for 79% of species, and no species produced more than 4 Mg ha^{-1} biomass. In general, the mild zone of the semiarid region appears more conducive to CC growth compared to the cold zone because CC species generally produced more biomass.

Warm Zone of the Semiarid Region

In the warm zone (USDA hardiness zone >7) of the semiarid region, CC biomass production ranged from 1.9 to 7.4 Mg ha^{-1} (Fig. 5). Biomass production of CCs was in this order: two-species mix > cowpea > barley > sorghum > oat > rye > complex mix > radish > pea > annual ryegrass > others. Note that sorghum, complex mix, radish, and pea all had < 3 observations. The most studied CC was rye, followed by hairy vetch > barley = oat > rapeseed. The species that both produced large quantities of biomass and were commonly studied were rye and oats, both of which were also top biomass producing species in the mild zone. However, both species produced over 1 Mg ha^{-1} (1.8 Mg ha^{-1} for rye and 1.2 Mg ha^{-1} for oats) more biomass in the warm zone than in the mild zone. All species produced at least 1 Mg ha^{-1} biomass, 92% produced at least 2 Mg ha^{-1}, and 50% produced at least 4 Mg ha^{-1}. Compared to other temperature zones in the semiarid region, this zone appears to have the most potential for CC biomass production.

Summary for Semiarid Temperate Region

In the semiarid region, CC biomass production increased as temperature increased, with greater numbers of species producing at least 2 or 4 Mg ha^{-1} biomass as temperature increased (Table 1). In the cold zone of the semiarid region, low biomass production was common; however, peas, radish, and complex mix were some of the top biomass producing species. In the mild region pea and radish along with oat, two-species mix, and rye were the highest biomass producing and most common species. Similar to the mild zone, rye, and oat were high biomass producing and commonly studied species. Rye, similar to the humid zone, produced substantial biomass in all three zones (cold = 2.1 Mg ha^{-1}, mild = 2.5 Mg ha^{-1}, warm = 4.3 Mg ha^{-1}), although it was not the most common in the cold zone.

In some areas of the semiarid region, such as those with <500 mm mean annual precipitation, balancing water availability between CCs and main crops can be critical. To illustrate this concept, we first describe CC effects on water availability in a relatively humid climate and then contrast these with areas with less water availability in drier parts of the semiarid region (<500 mm precipitation). At a site receiving about 950 mm annual precipitation under maize–soybean rotation, a winter rye CC increased plant available water by 21 to 22% and increased water content at field capacity by 10 to 11% after 13 yr of CC management (Basche et al., 2016). The use of rye CC did not affect main crop yield or main crop biomass yield in any measurement year, regardless of whether the year was dry or wet. By contrast, in two semiarid locations with <500 mm of precipitation, winter wheat yield decreased by about 10% when following a CC (Nielsen et al., 2016). The reduction in winter wheat yield was attributed to reductions in water availability caused by CCs. Similarly, in another semiarid location with <500 mm of precipitation, CC species with lower biomass production had the smallest effects on winter wheat yield due to lower water use by the CC (Holman et al., 2018). For example, Holman et al. (2018) found that for every 0.13 Mg ha^{-1} increase in CC biomass production, plant available water decreased by 1 mm, and for each 1 mm reduction in available water, wheat yield decreased by 0.055 Mg ha^{-1}. These studies in semiarid locations with <500 mm annual precipitation suggest that CC biomass production may substantially reduce crop yields.

FACTORS AFFECTING COVER CROP BIOMASS PRODUCTION

Our review suggests that many factors influence CC biomass production (Fig. 1). These include CC growing season duration, planting method, seeding rate, tillage method, and others. In this section, we highlight how management and environment influence CC biomass production.

Cropping System Effects on Cover Crop Biomass Production

Cropping systems vary among regions and can significantly affect CC biomass production, thus, we will discuss cropping system effects on CC biomass production by climate and CC species. For discussion purposes, we categorized the main crops into groups. Monocropped systems were classified into small grains, maize for grain and sorghum (hereafter referred to as maize), silage or seed maize, vegetables, rice (*Oryza sativa* L.), and other systems, which included crops that generally produce low biomass such as soybean or cotton. We distinguished among four types of diversified rotations: (i) maize–other systems: maize followed by other systems crop such as soybean; (ii) maize–other systems crop-small grain: maize followed by other systems crop such as soybean followed by a small grain; (iii) maize–small grain rotation: maize followed by a small grain such as wheat; and (iv) small grain-other systems: small grain followed other systems crop such as soybean.

Cover crop biomass production by cropping system was in this order: vegetables > small grain-other systems > maize–other systems-small grain > other systems > maize > small grain > others (Fig. 6). Cover crop biomass production was most commonly reported in maize > small grain > vegetables > other systems > maize–other systems > maize for silage or seed > others. This suggests that the most common systems, such as maize and small grain, may not allow for the highest biomass production. All systems except maize for silage or seed produced at least 2

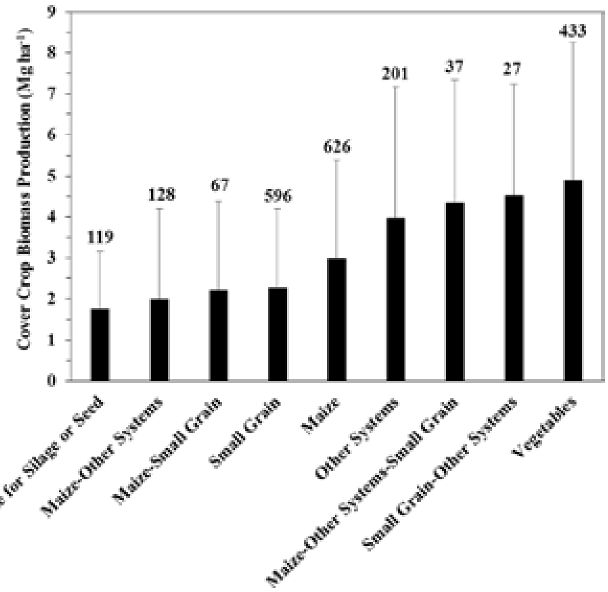

Fig. 6. Influence of cropping system on cover crop biomass production. Bars are standard deviation of the mean. Values above bars are the number of observations in that cropping system. Other systems included crops that generally produce low biomass such as soybean or cotton.

Mg ha^{-1} CC biomass. Maize–other systems-small grain, small grain-other systems, and vegetables were the systems to produce at least 4 Mg ha^{-1} CC biomass. Figure 6 suggests other systems, some diversified systems, and vegetables may allow for greater CC biomass production; however, this likely differs greatly be CC species, thus we next discuss the influence of cropping system on CC biomass production by CC species.

Grain, Seed, and Silage Maize Systems

Cover crop biomass production under maize ranged from 0.5 to 4.4 Mg ha^{-1} (Fig. 7A). Under grain maize, CC biomass production was highest from two-species mix, followed by crimson clover > sunn hemp > hairy vetch > pea > rapeseed > rye. This suggests that legumes and rye produce the most biomass in grain maize systems. The most commonly planted species were rye > two-species mix > hairy vetch > crimson clover > others. About 65% of the CC species planted in maize systems produced at least 2 Mg ha^{-1} biomass, but only 5% produced at least 4 Mg ha^{-1}. Under maize silage or seed, CC biomass production ranged from 0.6 to 3.6 Mg ha^{-1}, and was in this order: red clover > oat > annual ryegrass > rye > radish > hairy vetch > complex mix > two-species mix > others. It should be noted that rye, complex mix, two-species mix, and triticale were the only CC species with at least 10 observations. Thus, CC biomass production for the most studies species was in this order: rye > complex mix > two-species mix > triticale. Rye and two-species mix were assessed in both types of maize systems and appeared to be the CC species most likely to produce significant quantities of biomass.

Diversified Cropping Systems

Diversified systems included maize–other systems, maize–small grain, small grain-other systems, and maize–other systems-small grain. In these systems, many CC species have insufficient observations to allow ranking of CC biomass production; therefore, we focus on the species with at least five observations.

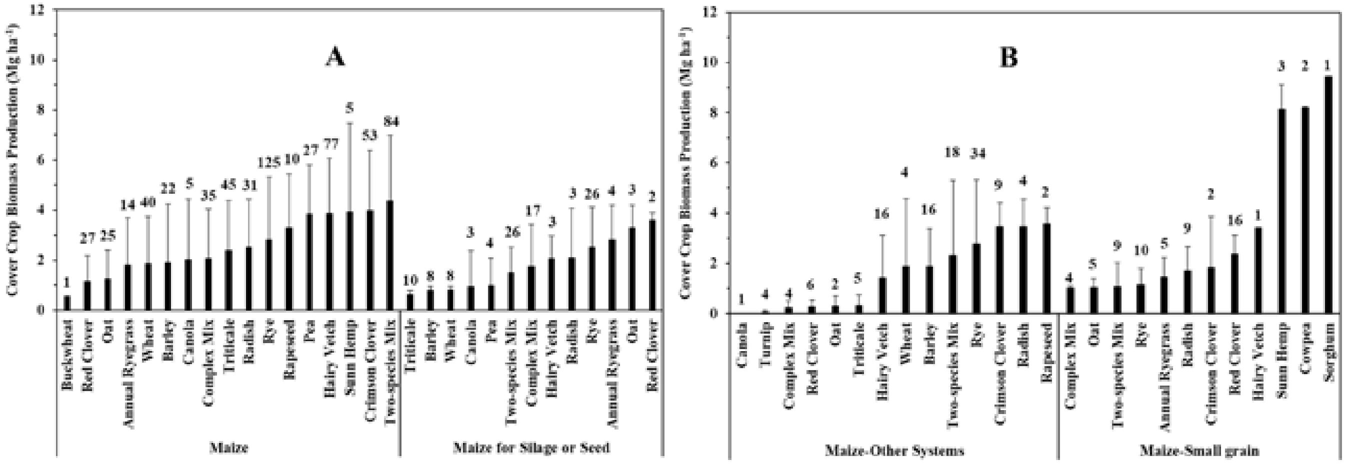

Fig. 7. Influence of cropping system on cover crop biomass production by cover crop species in maize and maize for silage or seed (A) and maize–other systems and maize–small grain (B). Bars are standard deviation of the mean. The values above the bars are the number of observations. Other systems included crops that generally produce low biomass such as soybean or cotton.

In maize–other systems, CC biomass production was in this order: crimson clover > rye > two-species mix > barley > others (Fig. 7B). Rye, two-species mix, barley, and hairy vetch were the most commonly evaluated species. However, rye and two-species mix were the only two species to have high biomass production and commonly studied. Under maize–small grains, most species had few observation (Fig. 7B); however, biomass production was in the following order: red clover > radish > annual ryegrass > rye > two-species mix > others. Red clover was common in this diversified system as it was often interseeded with the small grain and allowed to grow until maize planting. While rye may be a common CC in the maize–small grain system, it does not appear to be the most successful CC species based on biomass production. In small grain-other systems rotation, few CC species had more than five observations. These were two-species mix and rye. Two-species mix produced 6.6 ± 1.7 Mg ha^{-1} biomass (12 observations) while rye produced 1.8 ± 2.7 Mg ha^{-1} biomass. In maize–other systems-small grain rotation, only triticale and canola had more than five observations. Mean biomass production for triticale was 7.3 ± 1.4 Mg ha^{-1} (10 observations) and for canola was 0.9 ± 0.2 Mg ha^{-1} (seven observations). Cover crop species assessed in diversified systems were highly variable, with many having few observations for comparison, but it does appear that two-species mix was the most common and highest biomass producing species across most diversified cropping systems.

Other Cropping Systems, Small Grain, and Vegetables

Under other systems, CC biomass production ranged from 0.8 to 5.5 Mg ha^{-1} (Fig. 8). Cover crop biomass production was in this order: red clover > rye > two-species mix > rapeseed > hairy vetch > oat > radish > crimson clover > annual ryegrass > pea > others. The most common CCs species in other systems were rye > wheat > two-species mix = hairy vetch = oat > crimson clover. The species that both had the highest biomass production and were the most common was rye followed by two-species mix, hairy vetch, and oat, which are species similar to those planted in maize systems. About 86% of CC species produced at least 2 Mg ha^{-1} biomass, and about 29% produced at least 4 Mg ha^{-1} biomass, indicating that other systems can allow for greater biomass production than maize for grain or silage and seed.

Under small grain, CC biomass production ranged from 1.0 to 6.3 Mg ha^{-1} (Fig. 8). The highest biomass-producing CC species were sorghum > millet > complex mix > triticale > sunn hemp > oat > wheat > rye > buckwheat > barley > others. The most commonly evaluated CCs were red clover > pea > hairy vetch > complex mix > rye = annual ryegrass > rapeseed > others. The most commonly planted high biomass producing species were complex mix and rye. Rye was common to maize systems and other systems in terms of number of observation and was among the high biomass-producing species, but not complex mix. About 62% of CC species produced at least 2 Mg ha^{-1} biomass and about 10% produced at least 4 Mg ha^{-1} biomass. This indicates that small grain systems can be a lower biomass-producing system compared to other systems, but similar to maize depending on management and CC species.

Under vegetables, CC biomass production ranged from 2.1 to 7.7 Mg ha^{-1}. Cover crop biomass production was in this order: sunn hemp > complex mix > sorghum > two-species mix > cowpea > rye > millet > barley > wheat > triticale > others. The most commonly planted CC species were rye > two-species mix > oat > hairy vetch > radish > millet > sorghum > crimson clover > rapeseed > others. The most common and highest biomass producing species were, therefore, two-species mix, rye, sorghum, and millet. Based on these rankings, rye and warm-season grasses like sorghum and millet are well-suited for use as CCs in vegetables. Except for rye and two species mix, these four species (sorghum, millet, two-species mix, and rye) are different from maize and other systems, and small grain cropping systems previously discussed. All species produced at least 2 Mg ha^{-1} biomass, about 57% produced at least 4 Mg ha^{-1}, while about 24% produced at least 6 Mg ha^{-1}, indicating that vegetable systems have potential for high biomass production compared to all other cropping systems.

Summary of Cropping System

Overall, CC biomass production was in this order: vegetables > other systems > maize > and small grains. Some diversified systems also produced substantial quantities of CC biomass, but their assessment is more difficult due to the relatively smaller set of observations. Under all systems, rye was a common species

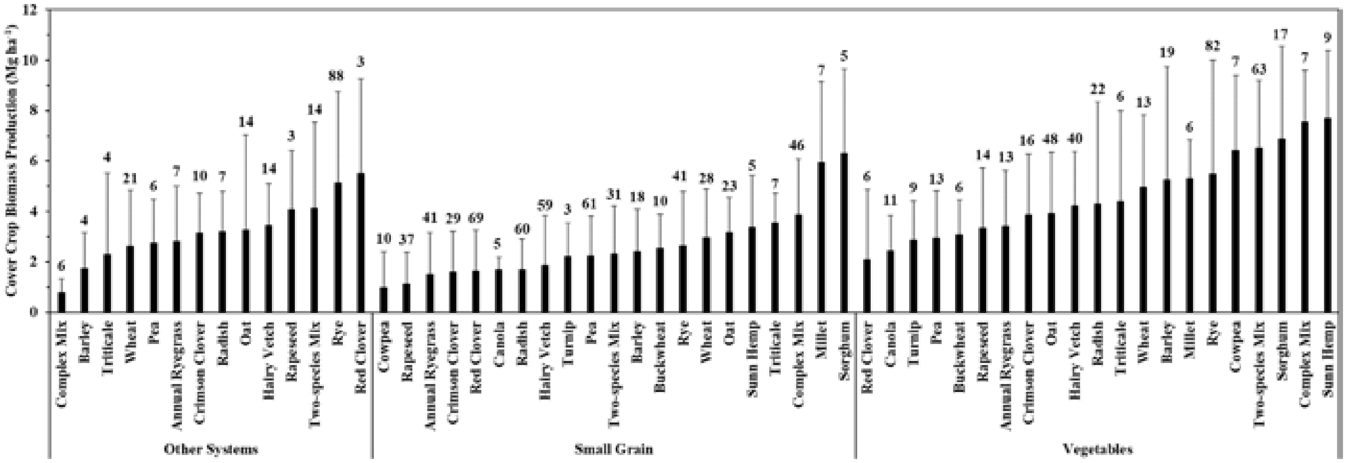

Fig. 8. Influence of cropping system on cover crop biomass production by cover crop species in other systems, small grain, and vegetables. Bars are standard deviation of the mean. The values above the bars are the number of observations. Other systems included crops that generally produce low biomass such as soybean or cotton.

with high biomass production. In maize and other systems, hairy vetch was a common, high-biomass producing species. Some types of mixes were well-suited to small grains and maize systems. However, vegetables, which generally had the highest CC biomass production, included the common species rye, but also two warm-season grasses, sorghum and millet, which produced 5 to 7.7 Mg ha^{-1} biomass. The biomass production of CCs in these different cropping systems likely depends on management, including planting method, planting date, and termination date, which will be the next factors discussed.

Planting Method

Cover crop seeding occurs through two primary methods: drilling and broadcast seeding. Broadcasting means seeds are spread and left on the soil surface without incorporation, although sometimes light harrowing is used to cover seeds with soil and crop residues. Broadcast seeding of CCs occurred in 18% of observations. Drilling CC by placing the seeds below the soil surface was the most common planting method (57% of the observations). The remaining observations did not specify a seeding method. Mean biomass production was 3.39 ± 2.93 Mg ha^{-1} for drilling, while it was 2.56 ± 2.16 Mg ha^{-1} for broadcast. It appears that drilling generally results in greater CC biomass production than broadcast seeding, likely due to improved seed placement and increased seed to soil contact; however, alternative broadcast and interseeding methods deserve further investigation to better understand establishment mechanisms that could increase biomass production. We discuss different types of interseeding or drilling under the "Planting Date" section, because both are closely related to planting date.

Growing Season Duration

Growing season duration can significantly affect CC biomass production. In other words, planting and termination dates can be important determinants of CC biomass production. Figure 9 shows the combined effect of planting season (spring, summer, or fall) and termination season on CC biomass production. The most common planting and termination pairing was fall planting with spring termination (38% of observations), followed by summer planting and fall termination (19% of observations). Other planting and termination combinations comprised the remainder of the total observations. The highest CC biomass production (4.2 Mg ha^{-1}) occurred for fall planting with spring or summer termination. Cover crop biomass production was 4.3 Mg ha^{-1} for summer planting with summer termination (includes summer planting and termination within the same summer and termination the following summer). Cover crop biomass production was lowest with fall planting and termination. These data indicate that timing CC planting and termination to achieve the longest growing season possible can optimize biomass production.

Data from individual case studies support broad interpretations across all studies. For example, in Alabama (humid and warm), grass CCs planted in November and terminated in late April produced 67% more biomass compared to late March termination (Balkcom et al., 2013). Similarly, in South Carolina (humid and warm), mid-October planting of rye increased CC biomass production by 74% compared to early December planting, and early November planting increased biomass production by 57% compared to early December planting (Bauer and Reeves, 1999). Growing season depends on climate. In climates with short growing seasons, such as the northern latitudes, timing of CC management may be critical to CC biomass production.

Planting Date

Planting date may impact CC biomass production. Different planting dates include interseeding early in during growing season, interseeding just before harvest, planting after a short-season or early-harvested crop, and post-harvest planting. In this section, we discuss the effects of planting date on maize, small grain, vegetables, and the other systems group because these cropping systems have sufficient observations of CC biomass production to assess the effect of planting date.

Seeding Early in the Growing Season

Drilling and broadcast interseeding were used occasionally to interplant CCs at the time of or shortly after primary crop planting. Based on literature, the productivity of CCs when planted early in the season depended on the cropping system. Under maize, spring-planted CCs produced about 1 to 1.5 Mg ha^{-1} biomass, while summer or fall-planted CCs produced < 3.9 Mg ha^{-1} (Fig. 10). Under small grains, spring-planted CCs (1.6 to 2.7 Mg ha^{-1}) produced lower biomass than

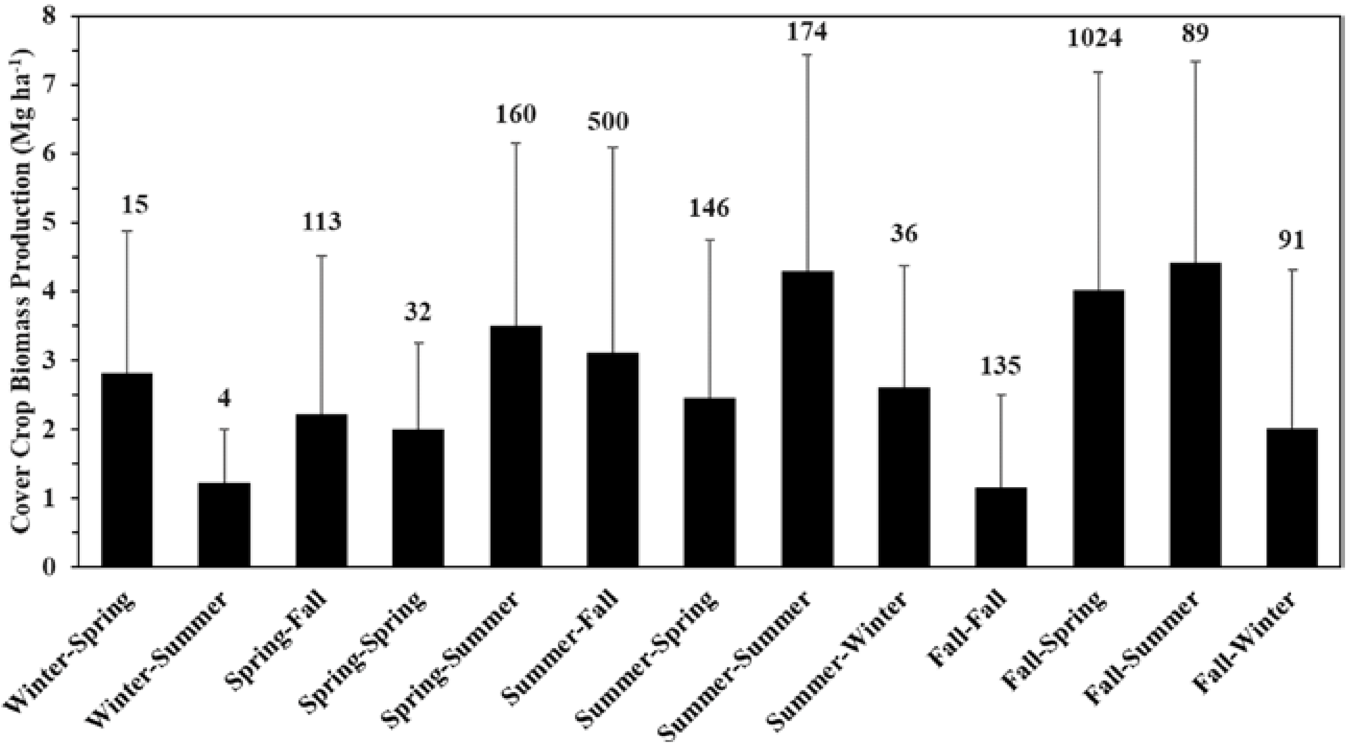

Fig. 9. Influence of planting and termination season on mean cover crop biomass production. Bars are standard deviation of the mean. Values above bars are the number of observations.

summer-planted CCs (up to 3.7 Mg ha^{-1}). Under vegetables, spring seeding CCs (5.7 to 8.1 Mg ha^{-1}) produced as much biomass as fall or summer seeding (up to 6.1 Mg ha^{-1}) depending on termination date. The greater CC biomass production with early seeding could be primarily due to optimum moisture conditions (Cicek et al., 2014) and temperature for germination. The early seeding gives CCs an advantage over late summer or fall growth compared to CCs drilled after harvest.

Specific examples of seeding CCs early in the growing season show variable biomass production. When CCs are interseeded, CC biomass production was 1.05 Mg ha^{-1} when drilled into spring barley (Sapkota et al., 2012) and 1.54 to 5.04 Mg ha^{-1} when broadcast 2 mo after planting soybean or a month before harvest of spring barley (Samarajeewa et al., 2006; Petersen et al., 2011). Cover crops may also be drill-interseeded when maize is at V3 using a high-clearance drill. This method may result in CC biomass production of 0.008 to 2.47 Mg ha^{-1}, depending on time of year and location (Curran et al., 2018).

In winter wheat systems, interseeding cool-season legumes such as red clover in early spring versus planting after harvest in mid-summer can extend the growing season for CCs and improve water availability (Gaudin et al., 2014). In colder climates, interseeded red clover was more productive than CCs planted after wheat harvest (Cicek et al., 2014). In temperate climates, red clover produced between 0.8 and 5.2 Mg ha^{-1} in the fall (Schipanski and Drinkwater, 2011; Amossé et al., 2014; Koehler-Cole et al., 2017) and between 0.4 and 5.5 Mg ha^{-1} in the spring after overwintering (Koehler-Cole et al., 2017).

Interseeding before Primary Crop Harvest

Interseeding before primary crop harvest is one method of potentially increasing CC biomass production compared to drilling after harvest of the main crop. In maize, summer-planted CCs (1.49 to 2.35 Mg ha^{-1}) produced as much or more biomass as fall-planted CCs (0.96 to 3.86 Mg ha^{-1}), depending on termination date (Fig. 10). Similarly, in the other cropping systems category, summer-planted CCs (about 1 to 3 Mg ha^{-1}) can produce less biomass than fall-planted (about 1.2 to 6.8 Mg ha^{-1}). Under vegetables, CC biomass production was greater with summer-planted (4.28 Mg ha^{-1}) than fall-planted CCs (3.96 Mg ha^{-1}). These data suggest that interseeding CCs prior to primary crop harvest can result in similar or greater CC biomass production than planting after harvest depending on cropping system.

A specific type of broadcast seeding is aerial interseeding where CCs are spread by airplane or broadcast by high-clearance seeders on a small scale into maturing stands of main crops. Aerial seeding of rye in the fall in Nebraska 1 to 2 mo before harvest of the main crop may result in biomass production of 1.47 Mg ha^{-1} (Blanco-Canqui et al., 2017), which is within the range of CC biomass production observed across all studies with broadcast seeding. Aerial seeding of rye into maize silage, grain maize, or soybean in a more northern climate of Minnesota, led to fall biomass production of 0.27 Mg ha^{-1} in maize and 0.17 Mg ha^{-1} in soybean (Wilson et al., 2013). Aerial seeding disadvantages include seed interception by leaves or in the whorls of maize plants, proximity to utility poles, wires, wooded areas, and availability of aircraft, as well as cost of increased seeding rates. A method to increase success of broadcast interseeding is to use a high clearance interseeder with drop hoses to place the CC seed near the soil surface where the seed will fall below the majority of the leaves. However, this method requires driving an implement through the field when the primary crop is growing or maturing. This could damage the primary crop and reduce yield.

Planting CCs before harvest of main crops, when these primary crops are senescing, may not affect main crop yield; however, planting during vegetative growth stages may reduce

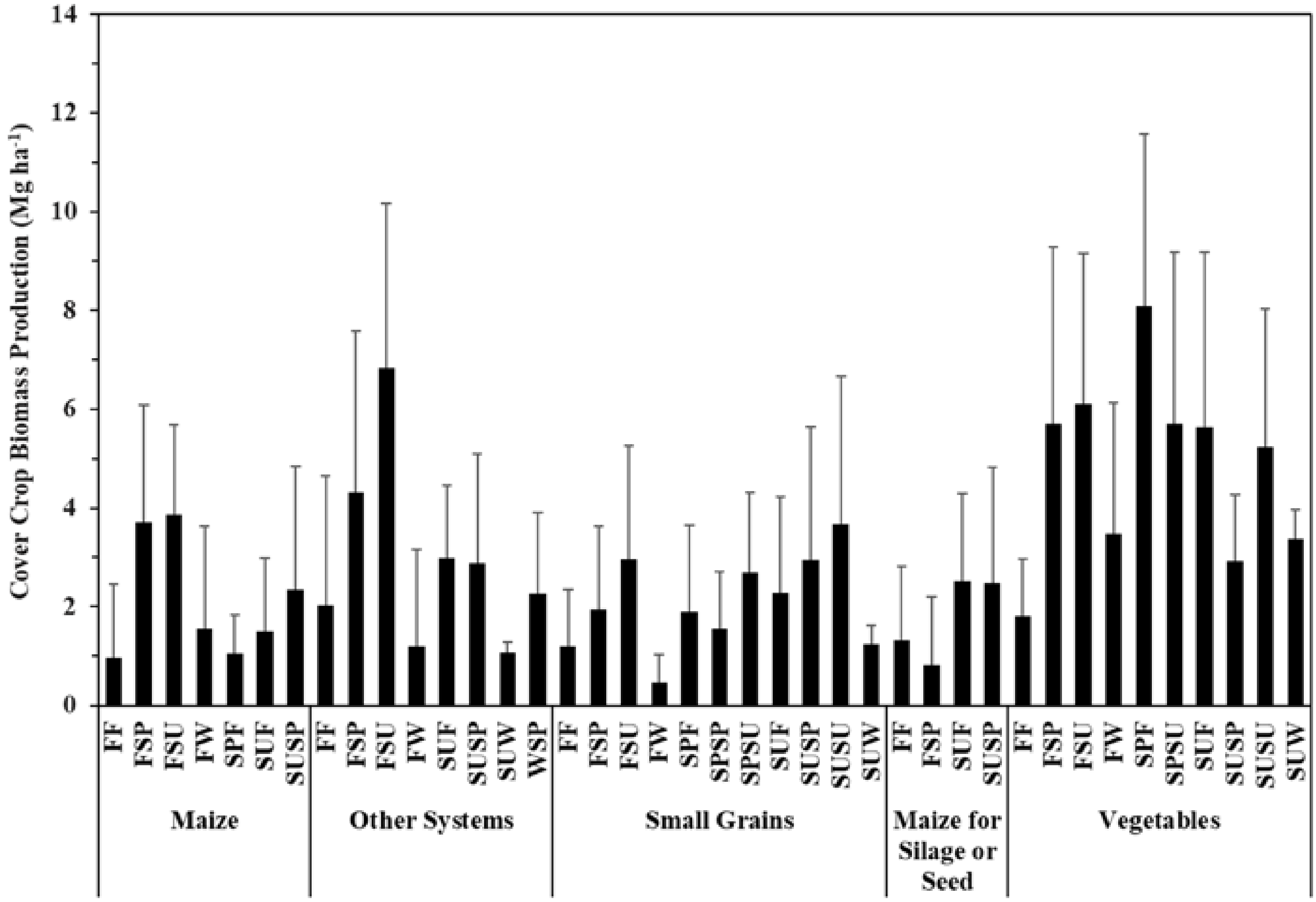

Fig. 10. Influence of planting and termination season and cropping system on mean cover crop biomass production. Bars are standard deviation of the mean. Values above bars are the number of observations. Other systems included crops that generally produce low biomass such as soybean or cotton. F, fall; SP, spring; SU, summer; and W, winter.

yields. This may depend on timing of seeding (Curran et al., 2018). For example, planting after the V5 growth stage in maize did not negatively impact maize yield, but seeding at V2 reduced yield (Curran et al., 2018). Planting pre-harvest may be a viable strategy to increase length of season and CC biomass production using the emerging technologies such as aerial and high-clearance interseeders.

Seeding after Short-Season or Early-Harvested Crop

Planting CCs in summer or early fall after winter wheat, seed maize, and silage maize can lead to greater CC biomass production than planting after harvest in mid or late fall. When CCs were planted after small grain harvest, CC biomass production ranged from 2.3 to 3.7 Mg ha^{-1} and after silage or seed maize, CC biomass production averaged about 2.5 Mg ha^{-1} when planted in summer (Fig. 10). Cover crop biomass production with fall planting and spring or summer termination averaged 3.8 Mg ha^{-1}, which is similar to planting after a short-season or early-harvested crop. A specific example of CCs planted in early August, after winter wheat, showed biomass production 62% greater than CCs planted in late August (Sturm et al., 2017). In some locations, warm-season CC biomass production was 5.5 to 8.25 Mg ha^{-1} when planted after winter wheat harvest in July (Blanco-Canqui et al., 2011; Keene et al., 2017). After silage maize, CC biomass production can be as high as 4.7 Mg ha^{-1} when planted shortly after maize silage harvest and terminated in spring (Tollenaar et al., 1992; Kuo et al., 1997; Krueger et al., 2011; Murrell et al., 2017). Studies evaluating CC biomass production when planted after seed maize are scarce (Belfry and Van Eerd, 2016). Planting after a short-season or early-harvested crop may produce large quantities of biomass depending on location and management.

Post-Harvest Seeding Timing

The timing of post-harvest seeding can prove critical to CC establishment. Planting early maturing primary crop cultivars could allow for earlier seeding, but regardless, delaying even 1 or 2 wk appears to significantly impact CC biomass production. For example, in Maryland (humid and warm), planting rye in mid-September and terminating in early May increased CC biomass production by 55% compared to early April termination (Clark et al., 1994). In South Carolina (humid and warm), rye CC biomass production, when planted in mid-October was 74% higher than when planted in early December (Bauer and Reeves, 1999). Similarly, oat CC biomass production, when planted in mid-October at the same location was 73% higher than when planted in early November. A study in Pennsylvania found that planting rye CC in early October and terminating in early June increased biomass production by 95% compared to mid-October planting and terminating in early May (Duiker, 2014). Overall, the longer the growing season with conditions conducive to growth, the greater the biomass production.

Termination Date

Modifying CC termination dates to allow CCs to grow longer will likely result in greater CC biomass production. However, this must be balanced with primary crop yield, as later termination may impose penalties on crop yields particularly in years when dry periods occur during critical crop development stages (Clark et al., 1994; Ruis et al., 2017). Previous studies found that late CC termination dates increase CC biomass production after maize and small grains by up to 94% (Table 2). For example, biomass production was 2.93 Mg ha^{-1} lower for crimson clover, 2.97 Mg ha^{-1} lower for hairy vetch, and 1.33 Mg ha^{-1} lower for pea when terminated in late April rather than mid-May in North Carolina (Liebman et al., 2018). One concern with late termination is reductions in primary crop yields potentially due to CC water use . One study investigating CC termination effects on main crop yields in two Maryland maize systems found that CCs terminated in early or mid-May instead of early or mid-April increased maize yield by 14 to 20% (Clark et al., 1994). However, in two Nebraska studies under continuous maize, CCs terminated at maize planting reduced maize yield by 6 to 9% in 1 of 3 yr compared with CCs terminated about 30 d prior to maize planting (Ruis et al., 2017). This reduction in maize grain yield was likely due to a dry period when maize plants were young, or to microbial activity associated with the fresh CC materials that immobilized soil nitrogen. With careful management of soil water, late termination of CCs can increase CC biomass production with few negative effects on main crop yields.

Combining Planting and Termination Dates

Planting early and terminating late could greatly extend the CC growing time and thus increase potential CC biomass production, but limited research has explored this hypothesis. In maize systems in Pennsylvania (humid and mild region), early planting and late termination allowed for CC biomass production between 1.51 and 8.09 Mg ha^{-1} (Duiker, 2014). Biomass production was greater with cool-season grasses compared to other CC groups like legumes. In another study in Pennsylvania, rye CC planted about 1 mo later (mid-Oct instead of mid-Sept) reduced biomass production by about 1.9 Mg ha^{-1} across all termination dates (Nord et al., 2012). Similarly, in spring for every 10 d (approximately) of CC growth, about 1.75 Mg ha^{-1} additional biomass may be produced (Nord et al., 2012). Thus, growing season length, through manipulation of both planting and termination dates can impact CC biomass production in the humid region. In drier locations, such as in southwestern United States (semiarid and warm region), planting a hairy vetch CC in early Sept with termination in mid-May could lead to biomass production of 4.6 Mg ha^{-1} compared to terminating in mid-Apr with 3.18 Mg ha^{-1} (Guldan and Martin, 2003). However, CC biomass production was < 0.2 Mg ha^{-1} when planted in early November, regardless of termination timing. Since planting CCs early and terminating late increase the CC growing season, this strategy can offer promise to increase CC growth in cold regions (USDA hardiness zone < 5) where the growing season is already short. In warm regions, planting CCs early and terminating late can take advantage of the natural long growing season. However, in semiarid regions, extending CC growing time may not work as the CCs may use water intended for the primary crop, thereby reducing crop yields. In humid regions, competition and CC water use are of less concern except in dry years.

Seeding Rate

Seeding or target plant density (plants m^{-2}) can directly affect CC biomass production because it determines the number of plants per unit area. Three studies specifically evaluated the influence of seeding rate on CC biomass production. In California (semiarid and warm region), seeding a rye CC in vegetable systems at rates of 90, 180, and 270 kg ha^{-1} increased CC biomass production by 26 to 50% (Boyd et al., 2009). In a humid and warm location, two warm-season legumes, cowpea and sunn hemp were planted at different seeding rates (Collins et al., 2008). For both species, doubling seeding rate increased CC biomass production. For example, increasing the sunn hemp seeding rate from 20 to 40 plants m^{-2} increased CC biomass production from 6.7 to 9.4 Mg ha^{-1}, while increasing seeding rate from 40 to 80 plants m^{-2} increased CC biomass from 9.4 to 10.5 Mg ha^{-1}. This suggests that CC biomass production increased linearly before it reached a plateau where additional seed did not necessarily mean substantially increased in biomass production.

Increasing seeding rates has both positive and negative aspects in terms of economics, ecosystem services, and crop yields. Lower CC seeding rates may be favorable from an economic standpoint, particularly for costly seed. However, the lower seeding rate may not be favorable for increasing soil C due to lower biomass input and/or less weed control. For example, increasing seeding rates may reduce weed biomass density or production (Collins et al., 2008; Boyd et al., 2009). Use of higher seeding rates can result in quicker achievement of high levels of biomass. For example, in a semiarid and warm region, rye CC planted at 180 kg ha^{-1} produced about 4 Mg ha^{-1} biomass about 2.5 mo after seeding compared to 3.3 Mg ha^{-1} when planted at 90 kg ha^{-1} (Boyd et al., 2009). Using higher seeding rates for interseeding may also negatively impact main crop yield. For example, doubling seeding rates of winter wheat and ryegrasses reduced barley crop yields, even at half rates (Kankanen and Eriksson, 2007). Red clover, however, generally did not significantly reduce yields compared to no CC. Data assessing non-interseeded CC seeding rates on main crop yields are unavailable in the studies we reviewed. In summary, use of higher seeding rates increased CC biomass production and may provide benefits for weed control through quicker establishment of high levels of biomass; however, it could reduce primary crop potentially due to CC water use or competition between the primary crop and CC when interseeded.

Tillage Method

Cover crops are managed under different tillage systems with no-till and different combinations of tillage (i.e., chisel-disk) being the most common practices. Tillage was more common (61% of observations) than no-till (20% of observations) across all studies. Remaining observations were reported across tillage systems (4% of observations). About 15% of CC studies did not specify tillage system used, which is a hindrance to assessing tillage effects on CC biomass production. In North America, 22% of observations were under no-till compared to 7% in Europe. Mean CC biomass production was 3.27 ± 3.04 Mg ha^{-1} under tilled systems and 3.13 ± 2.43 Mg ha^{-1} under no-till systems. The similarity in mean CC biomass production between tilled and no-tilled systems suggests that tillage may not greatly impact CC biomass production, at least in the studies reviewed. Individual studies also suggest that tillage may not generally

Table 2. Influence of cover crop (CC) termination date on CC biomass production by climatic regime, cropping system, and CC species. Means followed by different letters within the same study and planting time are statistically different and are based on significant differences calculated by the respective study authors.

Location	Temperature	Precipitation	Main crop	CC	Planting time	Termination time	CC biomass production	Reference
	°C	mm					Mg ha^{-1}	
Czech Republic	7.9	526	Wheat	Annual ryegrass	Mid to late Aug	Late Sept	0.07ab	Brant et al., 2011
				Radish			0.33d	
				Crimson clover			0.10abc	
				Annual ryegrass		Mid Oct	0.14a	
				Radish			1.24c	
				Crimson clover			0.40ab	
				Annual ryegrass		Early Nov	0.10a	
				Radish			0.99d	
				Crimson clover			0.59ab	
Nebraska	13	688	Maize	Rye	Early Nov	Early Apr	0.45b	Ruis et al., 2017
						Early May	4.12a	
	10	818			Late Oct	Early Apr	1.40b	
						Early May	3.00a	
Pennsylvania	10.1	1006	Cereals	Rye	Mid Sept	Early May	1.23a	Duiker, 2014
				Barley			0.79ab	
				Wheat			0.67b	
				Rye		Mid May	2.05a	
				Barley			1.60ab	
				Wheat			1.47b	
				Rye		Early Jun	4.09a	
				Barley			3.31b	
				Wheat			2.54c	
	11.5	1091	Cereals	Rye	Mid Sept	Early May	2.81a	
				Barley			2.21ab	
				Wheat			1.52b	
				Rye		Mid May	5.01a	
				Barley			4.01b	
				Wheat			3.01c	
				Rye		Early Jun	5.24a	
				Barley			4.98ab	
				Wheat			4.53b	
Illinois	10.9	1041	Maize	Rye	Early Oct	Early Apr	0.68	Crandall et al., 2005
						Mid Apr	1.53	
						Late Apr	2.66	
Maryland	12.4	1101	Maize	Rye	Mid Sept	Early Apr	2.90a	Clark et al., 1994
						Early May	6.39a	
	13.3	1160				Mid Apr	4.06a	
						Mid May	7.10a	
	12.4	1101		Hairy vetch		Early Apr	0.73b	
						Early May	4.76b	
	13.3	1160				Mid Apr	1.69b	
						Mid May	5.19b	
Maryland	12.4	1101	Maize	Rye	Late Sept	Late Mar	0.83c	Clark et al., 1997
						Early Apr	1.60b	
						Late Apr	2.92a	
				Hairy vetch		Late Mar	1.01c	
						Early Apr	2.06b	
						Late Apr	3.68a	
	13.3	1160	Maize	Rye	Oct	Late Mar	1.27b	
						Early Apr	1.63b	
						Late Apr	2.33a	
				Hairy vetch		Late Mar	2.96a	
						Early Apr	3.33a	
						Late Apr	3.36a	
South Carolina	17.5	1182	Maize	Wheat	Mid Nov	Mid Mar	0.89†	Bauer et al., 1998
						Mid Apr	4.58	
						Mid May	4.33	

† Study provided no means comparisons for comparing across dates.

affect CC biomass production. Studies that specifically compared tillage system effects on CC biomass production reported that tillage method did not generally affect CC biomass production in 20 of 22 studies using a variety of CC species including radish, hairy vetch, and rye (Yaffa et al., 2000; Sainju et al., 2005; Schomberg et al., 2006; Petersen et al., 2011; Evans et al., 2016). One of the two remaining studies found that CC biomass was 2.3 Mg ha^{-1} greater with strip till and 0.8 Mg ha^{-1} lower with conventional tillage compared to no-till (Jokela and Nair, 2016), while the other study found that tillage had variable effects ranging from neutral to increased biomass production (Price et al., 2016). Our review suggests that CC biomass production may not depend on tillage in most studies, which is somewhat surprising because tillage can move crop residues below the soil surface and can improve seed-soil contact compared to no-till. However, there are other factors to consider, including the soil benefits of no-till. For example, no-till can increase residue cover, water infiltration, and wet-aggregate stability, thereby reducing risks of water erosion (Kahlon et al., 2013) and wind erosion (Sharratt et al., 2012) and thus reducing nutrient loss from fields.

Cover Crop Cultivar

Cover crop cultivar may impact CC biomass production, where some species appear to have greater biomass production than others likely due to plant vigor and other factors. For example, Kaspar and Bakker (2015) found that, on average, triticale and wheat cultivars did not differ in biomass production. However, some rye cultivars ('Aroostook,' 'Maton,' and 'Elbon') produced 0.5 Mg ha^{-1} more than others ('Oklon,' 'Rymin,' and 'Wheeler'). Similarly, 'Aroostook' rye had 12% greater CC biomass production than 'Wheeler' rye (Mirsky et al., 2011). Not only do cultivar differences occur under grass-type CCs, but under different legumes as well. For instance, Harrison et al. (2006) found that some cultivars of cowpeas (e.g., 'UCR 1340') may produce 1 Mg ha^{-1} more than others ('Graham' and 'Lalita'). However, other cultivars did not differ in biomass production compared to the most commonly used cultivar 'Iron Clay'. It is important to consider that performance of one cultivar may not be consistent from site to site, with clear genotype by environment interactions. For example, 'Abruzzi' rye had lower biomass production than 'Wheeler' rye at one site, but the two cultivars were similar in biomass production at three other sites within the same state (Harrelson et al., 2007). The above discussion warrants testing different CC cultivars to select the most adaptable and highest-producing varieties for a given agroecoregion and potentially additional breeding for improved cultivars adapted to dominant cover cropping strategies.

Irrigation

Water availability is often a limiting factor for CC biomass production, particularly when planted in dry soils in summer or early fall. Wilson et al. (2013) found that precipitation within a week of seeding is critical to CC success. Thus, one or two irrigation events immediately after CC planting may improve CC emergence and biomass production. In our review, irrigation quantities ranged from 6 to 80 mm. However, in 41 observations, the researchers indicated they irrigated at establishment but did not report an amount. Cover crops irrigated in cropping systems of maize (n = 10), small grains (n = 17), other systems (n = 7), and vegetables (n = 18), among others (n = 5). Across all studies, irrigation of CCs at establishment resulted in CC biomass production of 4.72 ± 4.08 Mg ha^{-1}, while no irrigation resulted in biomass production of 3.32 ± 2.90 Mg ha^{-1}. This suggests that irrigation may increase CC biomass production by about 42% through facilitating CC establishment.

Table 3. Influence of irrigation during establishment on mean (+-SD) cover crop (CC) biomass production by CC group in humid and semiarid regions.

CC group	Non-irrigated	Irrigated
	Mg ha^{-1}	
Humid		
Brassica	2.71 ± 1.92	3.50 ± 0.90
Grass	4.03 ± 3.48	3.12 ± 1.38
Legume	3.37 ± 2.52	6.07 ± 4.63
Mix	3.92 ± 2.59	6.88 ± 8.37
Semiarid		
Brassica	1.75 ± 1.05	2.88 ± 1.79
Grass	3.26 ± 3.27	3.98 ± 2.98
Legume	2.16 ± 1.92	2.43 ± 2.09
Mix	2.34 ± 1.80	5.04 ± 2.67

Irrigation at establishment may be more beneficial in dry climates and for certain CC species. For example, as shown in Table 3, brassicas produced 1.13 Mg ha^{-1} more biomass with irrigation compared to no-irrigation, while in the humid region irrigating brassicas resulted in 0.79 Mg ha^{-1} greater biomass production. Similarly, for grasses and legumes in the semiarid region, irrigation increased biomass production by 0.3 and 0.7 Mg ha^{-1} (15 to 22%). Irrigation also increased legume biomass production by 80% in the humid region.

Few studies directly compared irrigation effects on CC biomass production in the same experiment. One such experiment in Colorado and Nebraska found that irrigation of 109 mm increased biomass production of rapeseed, oat, and pea CCs by 1.38 Mg ha^{-1} compared to no irrigation (Nielsen et al., 2015). In another example, aerially interseeding CCs into maize in Nebraska produced 1.47 Mg ha^{-1} of biomass when irrigated twice with 25 mm of water (Blanco-Canqui et al., 2017), which is similar to some non-irrigated and drilled CC biomass production in the state (Ruis et al., 2017).

The above review suggests that for drier regions and harder-seeded species like brassicas and legumes, irrigation can be beneficial to CC establishment, likely through the increase in water available for seed imbibition. However, irrigation use may be of concern in semiarid regions if the pumping of groundwater resources exceeds recharge, reducing water needed for sustained irrigation of the primary crop. While irrigating CCs can increase biomass production, tradeoffs including financial and environmental costs of irrigating CCs should be considered.

Fertilization

Fertilization of CCs may impact CC biomass production. Sixty-one studies evaluated the influence of N fertilization on CC biomass production (Table 4). Nitrogen fertilization rates varied from 7 to 392 kg ha^{-1} N. Across all 61 studies (n = 521 observations), mean CC biomass production was 3.76 ± 3.71 Mg ha^{-1} with fertilization and 2.09 ± 1.59 Mg ha^{-1} without fertilization. Since precipitation and CC group appeared to

Table 4. Influence of N fertilization on mean (+-SD) cover crop (CC) biomass production by mean annual precipitation and CC group.

CC group	Non-fertilized	Fertilized
	Mg ha^{-1}	
Brassica	1.50 ± 0.67	3.27 ± 1.74
Grass	1.70 ± 1.55	3.78 ± 4.01
Legume	3.36 ± 2.37	4.14 ± 3.93
Mix	2.20 ± 1.14	3.49 ± 3.43

interact with fertilization effects on CC biomass production, we explored N fertilization effects on CC biomass production by these factors. In the humid region, fertilization (3.97 ± 3.83 Mg ha^{-1}) increased CC biomass production by nearly 2 Mg ha^{-1} compared to no fertilization (2.13 ± 1.44 Mg ha^{-1}). However, in the semiarid region, fertilization appeared to have a lesser effect (1.96 ± 1.89 Mg ha^{-1} for non-fertilized vs. 2.09 ± 2.49 Mg ha^{-1} for fertilized). The lower response of CC biomass production to N fertilization in the semiarid region could be due to water limitations because N fixation is an energy-intensive, and thus, water-intensive process.

The influence of fertilization on CC biomass production by CC group is shown in Table 4. Fertilization with N had greatest impact on brassica and grass CC biomass production, which more than doubled with fertilization. Fertilization increased CC biomass production by about 1.3 Mg ha^{-1} for mixes and by about 0.79 Mg ha^{-1} for legumes. Legumes likely did not respond to N-fertilization as readily as other species due to their N-fixing capability. Fertilization with N can reduce legume CC biomass production. For example, CC biomass production of red clover decreased linearly from 2.17 Mg ha^{-1} with 0 kg ha^{-1} N, to 1.75 Mg ha^{-1} with 40 kg ha^{-1}, to 1.47 Mg ha^{-1} with 80 kg ha^{-1} N, and to 1.09 Mg ha^{-1} with 120 kg ha^{-1} N (Gaudin et al., 2014). Across legume CCs, for every increase in N fertilization by 1 kg, legume CC biomass production decreased by about 0.05 Mg ha^{-1} ($r = 0.33$; $p = 0.02$; $n = 52$).

Grass CCs may show rapid linear increases in biomass production with N fertilization. Rye CC produced 3.87 Mg ha^{-1} with 0 kg ha^{-1} N, 6.25 Mg ha^{-1} with 34 kg ha^{-1}, 7.46 Mg ha^{-1} with 67 kg ha^{-1} N, and 9.03 Mg ha^{-1} with 101 kg ha^{-1} N (Balkcom et al., 2013). Across all rye CCs, for every 1 kg increase in N fertilization, rye CC biomass production increased by 0.07 Mg ha^{-1} ($r = 0.40$; $p < 0.0001$; $n = 98$). Similar to irrigation, the use of fertilizers has a financial cost, and must be considered when assessing farm economics and ecosystem services provided by CCs; the latter are rarely recognized by subsidies or the marketplace.

RESEARCH NEEDS

We identified a number of research needs that would improve our understanding of CC biomass production: (i) Development of best management strategies for CC biomass production (planting and termination dates and others) by region and cropping system are needed to optimize potential soil health benefits and minimize negative impacts to crop yields; (ii) CC cultivar trials that assess biomass production are needed to determine which cultivars produce maximum biomass in certain agroecoregions, different CC cultivars may vary in biomass production as shown in several studies (Harrison et al., 2006; Harrelson et al., 2007; Mirsky et al., 2011; Kaspar and Bakker, 2015); (iii) altering current cropping systems to allow for greater CC growing seasons, such as the use of shorter-season cultivars or different main crop planting dates may aid in maximizing CC biomass production and provide additional CC benefits; (iv) studies directly comparing the influence of one or two irrigation events or use of fertilization at CC establishment under both drill and broadcast seeding should be conducted to determine the economical threshold levels of irrigation and fertilization for CC biomass production; (v) investigation into best CC mix composition is needed because CC mixes appear to produce different biomass levels in some locations (Clark et al., 1994; Little et al., 2004; Brennan and Smith, 2005; Brennan and Boyd, 2012; Hayden et al., 2015; Keene et al., 2017), but current combinations of mixes are generally inconsistent in CC species composition; and (vi) economic determinations of implementing CCs using different species and different management strategies are needed to identify best management practices for CCs from a financial standpoint.

SUMMARY AND CONCLUSIONS

Based on our review, CCs can produce significant amounts of biomass; however, the amount of biomass produced depends on multiple factors (Table 1). Overall, rye was the most common and most versatile species, and was among the top biomass producing CC species in multiple climates and cropping systems. In the humid region, CC biomass production was greatest for these most common species: complex mix, rye, two-species mix, radish, hairy vetch, sunn hemp, annual ryegrass, and cowpea depending on temperature. In the semiarid zone the most common species with greatest biomass production were: pea, radish, complex mix, rye, and oat. By cropping system CC biomass production was highest in vegetables, followed by other systems > maize > small grains. Rye was among the highest biomass producing and most common in most cropping systems.

Regardless of CC groups or cropping system, lengthening the CC growing season equates with greater biomass production. Early- to mid-fall CC planting with late spring or summer termination produces the most biomass in many locations. While planting early or terminating late can improve CC biomass production, it could reduce main crop yield, particularly when dry periods occur around planting and early development of the main crop. Additional practices that affect CC biomass production include irrigation and seeding method. Also, further research is needed to optimize CC biomass production cultivar and species choice by location and management, best CC management strategies, and prediction tools for termination timing, among other factors. Overall, while CCs can produce significant amounts of biomass, this production can vary with climate, CC group, main cropping system, and management.

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