Intercropping with Switchgrass Improves Net Greenhouse Gas Balance in Hybrid Poplar Plantations on a Sand Soil

In the Pacific Northwest, commercial hybrid poplar (Populus generosa Henry × Populus canadensis Moench.) is managed at low stocking densities under irrigation for high-value timber production. The objectives of this study were to measure greenhouse gas emissions (CH4, CO2, and N2O) during intercropping of switchgrass (Panicum virgatum L.) with hybrid poplar; estimate losses of fertilizer-N as N2O, and estimate global warming potentials (GWP) of the intercrop. Cumulative above-ground biomass-C of the poplar monoculture (PM) closely matched the four year growing season (GS) soil CO2-C emissions, while aboveground biomass of the switchgrass monoculture (SM) and intercrop (IC) exceeded GS CO2-C emissions by 14.1 Mg C ha⁻¹. Soil CH4-C uptake was not significantly different between treatments, while GS N2O-N emissions for PM were ~80% lower than both IC and SM. N2O emissions factors averaged 0.7% of the applied N-fertilizer. Cumulative contributions of CO2 emissions to GWP were offset by biomass-C resulting in a near zero balance (−5.1 Mg CO2eq ha⁻¹) for the PM, where, IC and SM sequestered significantly more CO2 resulting in a net GWP of −42.5 and −32.2 Mg CO2eq ha⁻¹, respectively. Intercropping with switchgrass can improve the net greenhouse gas balance of hybrid poplar. Continued research is needed on the effects of irrigated bioenergy production on GHG emissions in intercropped systems as they will become increasingly important as agricultural water use, water availability and quality are challenged by climate change.

Core Ideas
• A critical issue in the production of biofuels has been the competition with food crops
• Intercropping switchgrass and hybrid poplar was found to be a viable bioenergy production strategy
• Intercropped biomass production offset increases in GHGs and GWP
• N2O emissions factors averaged 1% of the applied N over the study

Major shifts in crop production will occur as farmers prepare to supply the demand for biomass feedstocks for production of renewable biofuels. These shifts will affect agroecosystem services related to water use, carbon storage, nutrient cycling and greenhouse gas (GHG) emissions that have direct effects on air, water, and soil quality (Popp et al., 2014). Perennial grasses are an important source of feed and fiber and are considered sustainable bioenergy crops because they have the capacity to produce large quantities of biomass, can be grown on marginal lands, improve soil quality and protect soils from erosion (Lemus and Lal, 2005; Sartori et al., 2006; Casler et al., 2009; Gelfand et al., 2013). Switchgrass (Panicum virgatum L.) is a prominent biomass crop for the US biofuel industry (Sanderson et al., 2007; Casler et al., 2009) because it yields well on a variety of soil types, is drought-tolerant, and has low fertility requirements (McLaughlin and Kszos, 2005; Lemus and Lal, 2005; Kimura et al., 2015). The root system of switchgrass has been shown to offset C losses and promotes C sequestration by adding a
A significant amount of organic matter to the soil (Ma et al., 2000a, 2000b; Liebig et al., 2005, 2008; Collins et al., 2010). A potential solution to offset this concern is to grow dedicated energy crops on marginal lands (Kang et al., 2013; Gelfand et al., 2013) or maximize land use by intercropping in alley cropping with perennial crop (Blasier et al., 2012; Cacho et al., 2015; Tian et al., 2016). Intercropping is the growing of two or more crops of different species or varieties in close proximity to maximize the capture of photosynthetically active radiation and enhance the yield of both species compared with their growth in monoculture. This biological synergism results in improved ecosystem services through the sharing of space, soil and water resources, mutual protection from pests, greater nutrient availability, and enhanced biodiversity of soil microbes, insects and animals (Power, 2010).

There are many examples of successful intercropping systems. These systems commonly include tree or other woody species often from tropical or semi-tropical environments within agroforestry production systems (Suresh and Rao, 1999; Nissen et al., 2001; Prasad et al., 2010), combined with annual food crops grown using low inputs (Gliesman, 2007; Lithourgidis et al., 2011; Gebru, 2015). Few studies of intercropping woody species with annual food crops in North America have been conducted (Thevathasan and Gordon, 2004; Rivest et al., 2009; Evers et al., 2010). Thevathasan and Gordon (2004) summarized 15 yr of intercropping research with ten tree species and four annual grain crops. They found younger tree stands did not reduce grain yields when intercropped. However, competition increased with older stands of hybrid poplars with all annual grain crops (Evers et al., 2010). Intercropping of trees with annuals was shown to improve N and C cycling (Allen et al., 2004; Fang et al., 2010), enhance wildlife habitat (Stainback and Alavalapati, 2004), and reduce erosion and ground and surface water contamination (Zamora et al., 2009; Bergeron et al., 2011).

Intercropping with perennial species is an additional option for forest landowners across the United States due to its potential for promoting environmental benefits and increase economic returns. Gamble et al. (2014) found that intercropping among rows of poplar and willows provided suitable conditions for establishment of several perennial biomass crops including switchgrass, prairie cordgrass (Spartina pectinata L.), alfalfa (Medicago sativa L.) and wheatgrass (Thinopyrum intermedium L.), but the potential for resource competition increased with time. Switchgrass and loblolly pine (Pinus taeda L.) interactions have been investigated in several intercropping studies established on the coastal plain of the southeastern United States (Cacho et al., 2015; Tian et al., 2015; 2016).

Several studies have shown the benefits of intercropping woody species and switchgrass on yield and soil properties (Blasier et al., 2012; Gamble et al., 2014; Cacho et al., 2015; Muwamba et al., 2015; Tian et al., 2016). These benefits result from a diversification of outputs and a shortened time to reach economic production (Holzmueller and Jose, 2012; Susaeta et al., 2012). Evers et al. (2010) reported that tree-based intercropping systems stored more C than conventional cropping systems by increasing C storage in the biomass of planted trees and increased soil organic matter storage through C inputs to the soil. Further, they suggested that tree-based intercropping in temperate regions not only sequestered atmospheric CO2, but also reduced N2O emissions compared with conventional monocultures.

Soils are an important source and sink of anthropogenic CO2, CH4 and N2O in terrestrial ecosystems. Changes in land use or cropping strategy can significantly affect the release of these gases and contribute to the greenhouse effect of warming global temperatures (Snyder et al., 2009; Signor and Cerri, 2013; IPCC, 2013). Nitrous oxide and CH4 produced in the soil are small compared with CO2 but have radiative forcing 298 and 25 times greater than CO2 respectively, over a 100 yr period (IPCC, 2013).

Emissions of CH4 from soil depends on the source and sink of C resources of soils under different land uses and is ubiquitous in temperate, tropical, boreal, grasslands and forests (Powlson et al., 1997; Le Mer and Roger 2001; Palm et al., 2002; USAFGGI, 2008). Nitrous oxide is emitted from ecosystems through microbiologically mediated pathways of nitrification and denitrification (Snyder et al., 2009; Signor and Cerri, 2013; IPCC, 2013). Agriculture is responsible for greater than 67% of N2O emissions, and result primarily from animal waste management and crop fertilization (IPCC, 2013; Gelfand et al., 2013). The magnitude of these emissions depends on management, climatic conditions, N fertilization, and availability of N and site soil properties (Smith et al., 2003; Signor and Cerri, 2013).

The Intergovermental Panel on Climate Change (IPCC) estimates that fertilized soils have an average N2O emission factor of 1% (range 0.3 to 3%) of the fertilizer N applied (IPCC, 2013). Emissions of N2O from N-fertilized agricultural fields has been found to range between 0.001 and 6.8% (Bouwman, 1996; Snyder et al., 2009; Signor and Cerri, 2013; IPCC, 2013). Adler et al. (2007) reported soil N2O emissions are the largest source of greenhouse gas emissions associated with bioenergy crop production. Oates et al. (2016) found N2O emissions from annual crops (corn, Zea mays L.; soybean, Glycine max L. Merr.; canola, Brassica napus L.) were 142% higher than from perennials (switchgrass; Miscanthus × giganteus; poplar (Populus spp.), and restored prairie), with fertilized perennials 190% higher than unfertilized perennials. Emissions ranged from 3.1 to 19.1 kg N2O-N ha⁻¹ yr⁻¹ for annuals and 1.1 to 6.3 kg N2O-N ha⁻¹ yr⁻¹ for perennials with N2O peak fluxes associated with precipitation and fertilization. Schmer et al. (2012) found CH4 emissions had a range of -3.8 to 2.4 g ha⁻¹ d⁻¹ for fertilized monoculture switchgrass and -6.8 to -3.8 g ha⁻¹ d⁻¹ for unfertilized switchgrass. Nitrous oxide flux was affected by N treatment, soil temperature and water filled pore space. The flux of N2O ranged from 0.24 to 8.6 g ha⁻¹ d⁻¹ for fertilized switchgrass. Few studies have evaluated greenhouse gas emissions from the intercropping of woody and perennial grasses such as switchgrass. Evers et al. (2010) reported mean N2O emission from monoculture and tree-based intercropping were 10.7 and 7.5 gha⁻¹ d⁻¹, respectively.
In the Pacific Northwest, commercial hybrid poplar (Populus generosa × P. canadensis) have been successfully managed at low stocking densities under irrigation for high-value timber production (Stanton et al., 2002). These plantations have been managed at a density of 1536 stems ha⁻¹ for 6- to 8-yr pulpwood rotations or at a density of 358 stems ha⁻¹ for 12- to 15-yr saw log rotations. The open understory created by low stocking rates can be used for the production of energy feedstocks; intercropped with perennial grasses such as switchgrass prior to canopy closure. We hypothesize that the intercropping of switchgrass with hybrid poplar significantly increases the flux of GHG but reduces the GWP under irrigated conditions due to increased biomass production. This study is the first in the Pacific Northwest on GHG emissions from the intercropping of switchgrass with hybrid poplar and provides early information on the effects of intercropping on GHG’s as the bioenergy industry develops. The objectives of this research were to (i) describe seasonal patterns of GHG fluxes (CH₄, CO₂, N₂O) during intercropping of switchgrass with hybrid poplar, (ii) estimate growing season losses of N₂O, and amount of N-fertilizer losses as N₂O, and (iii) estimate global warming potentials produced by intercropping vs monocultures of poplar or switchgrass.

METHODS AND MATERIALS

The hybrid poplar-switchgrass intercropping study was established on the GreenWood Resources Inc., Boardman Tree Farm, Boardman, OR (45°46’ N, 119°32’ W; elevation 192 m) in 2011. The site has a mean annual temperature of 11.7°C and during the winter months (November–March) receives an average of 170 mm precipitation as rain and snow (Fig. 1).

Crops grown in the region require irrigation. Soil at the field site is Quincy fine sand (mixed, mesic Xeric Torripsamments). Selected soil characteristics are presented in Table 1. Soil bulk density was determined using a 7.6-cm diameter impact core sampler according to Blake and Hartage (1986). Particle size was determined by the hydrometer method (Gee and Bauder, 1986), and pH and EC determined using the method of Robertson et al. (1999). Soil elemental concentrations were determined by the Mehlich 3 extraction method (Mehlich, 1984).

The experimental design was a randomized complete block comprised of two hybrid poplar clones—P. generosa (PC4) and P. canadensis (OP367)—planted within four experimental blocks. Main plots comprise three intercropping patterns and switchgrass cultivars assigned to subplots. The three levels of the intercrop were: (1) grass cultivars inter-planted with poplar trees (IC), (2) monocul-
ture grass cultivars (SM), and (3) monoculture trees (PM) (Fig. 2). Field plots comprised an area occupied by 60 poplar trees configured as 5 rows x 12 trees within each row that formed four intercropped areas. Each plot was planted in 2011 with 6 m x 3 cm diameter poplar poles obtained from the GreenWood Resources Inc., nursery, Boardman Tree Farm, Boardman, OR. Three switchgrass cultivars, ‘Kanlow’ (USDA-NRCS, 2011a), ‘Blackwell’ (USDA-NRCS, 2011b), and ‘Trailblazer’ (Vogel et al., 1991) were seeded at a rate of 11.2 kg pure live seed ha\(^{-1}\) on 10 June to 13 June 2011 using a 3 m (width) Tye Drill (Great Plains Manufacturing, Salina, KS) with double disk openers. Grass monocultures were randomized and planted adjacent to the intercropped plots with four replications.

All monoculture and intercropped switchgrass plots, received a blended dry granular fertilizer of 112 kg N ha\(^{-1}\) as urea (45–0–0), 28 kg P ha\(^{-1}\) as mono-ammonium phosphate (11–52–0), 112 kg K ha\(^{-1}\) as potash (0–0–60), and 56 kg S ha\(^{-1}\) as ammonium sulfate (21–0–24) in April and 112 kg N ha\(^{-1}\) as urea after the first harvest in July each year with a 3 m (width) Barber spreader (Barber Engineering Company, Spokane, WA).

Switchgrass was harvested annually in early July (1–8 July) and October (1–5 October) each year with a Hesston discbine swather (AGCO Corporation, Duluth, GA). Following cutting and before windrowing the switchgrass hay was aerated to speed drying with up to five passes of a New Holland tedder (New Holland Agriculture). The hay was then baled with a Case International Harvester 8555 baler (Racine, WI) and removed from the field. Aboveground biomass after wind rowing and tedding was collected from the center of each plot (5.6 m\(^2\)) and weighed to determine yield. Biomass dry

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**Fig. 2.** (a) Experimental design and (b) example of a replicate of the intercropping switchgrass and hybrid poplar set up, showing location of gas flux chambers among trees and monocultures. The blue dots represent locations of gas flux chambers. The photos show the area planted between poplar trees after harvest. Switchgrass monocultures were planted in replicated blocks (foreground).
matter production was determined for each plot using 0.5- to 1.0-kg subsamples dried at 50°C for up to 5 d until a constant weight was reached and biomass yields converted to a dry matter basis.

Annual hybrid poplar tree biomass yield was estimated using regression algorithms to obtain tree weight from measurements of tree age and clone from standing tree diameter and height. These algorithms were developed from previous destructive harvest sampling in the development of the poplar clones used in this study (personal communication, Brian Stanton, Greenwood Resources Inc.). Poplar leaf and branch biomass was also collected after leaf fall in November each year and were included in the estimates of aboveground biomass. Dried subsamples of switchgrass, poplar leaves and branches were ground with a Wiley mill (Thomas Scientific, Swedesboro, NJ) equipped with a 1-mm screen. Total C and N samples (0.2 g) were determined by dry combustion on an Elementar model Vario EL III CNS Analyzer (Elementar, Hanau, Germany). The C content of the leaves and branches varied from year to year so estimates of the aboveground biomass were based on the yearly analyses. Poplar C ranged from 0.45 to 0.51 g g⁻¹ in branches and 0.38 to 0.42 g g⁻¹ in leaves.

Weeds were controlled annually with glyphosate [N-(phosphonomethyl) glycine] at 13.0 g a.i. ha⁻¹ in late March during switchgrass dormancy. Irrigation was applied by solid set sprinklers positioned within the tree rows. Rain gauges were placed in each plot to quantify the amount of water applied over the growing season. The cumulative amount and duration of irrigation applied during the season was managed by Greenwood Resources Inc. with an average of 225 cm ha⁻¹ from April to October in the establishment year and increased to 300 cm ha⁻¹ by year four of the study determined from the rain gauge data.

Greenhouse Gas Flux Measurements:
CO₂, CH₄, N₂O

In situ GHG fluxes were measured using the closed static chamber method (Hutchinson and Mosier, 1981; Hutchinson and Livingston, 1993). Duplicate chambers were installed in each replicate of the P. g e n e r o s a (PC4) monoculture, Kanlow switchgrass/PC4 poplar intercropped treatment, and Kanlow switchgrass monoculture, and sampled according to the USDA-ARS GRACEnet (Greenhouse gas Reduction through Agricultural Carbon Enhancement network) protocols (Parkin and Ventera, 2010). Two base frames were inserted within each treatment replicate at the beginning of the growing season and remained in the field until removal prior to harvests and replaced afterward (Fig. 2). Chambers were placed in the center of each plot with replicates within 6 m of each other. Each base frame was a 30.5-cm diameter × 15-cm height PVC cylinder driven into the soil surface to a depth of 10 cm. Greenhouse gas fluxes were measured by fitting the chamber base frames with a vented PVC cap (30.5-cm inner diameter by 7.5-cm height) that contained a sampling port. The caps had a 2.5-cm diameter hole allowing air to exit and minimize air turbulence when caps were placed. The hole was sealed with a rubber stopper during the measurement period. Vegetation was removed from the chamber area and soil respiration measured.

Fluxes in the establishment year (2011) were measured weekly following irrigation events from June through September. In subsequent years soil fluxes of CO₂, CH₄ and N₂O were measured weekly throughout the growing season following irrigation events from April through September. Depending on the time of season, an average of 25 mm of water was applied at each irrigation event. The amount of irrigation water applied was calculated from a localized hybrid poplar crop model developed by Greenwood Resources Inc. (Gochis and Cuenca, 2000) and 25 yr of historical local AgriMet weather station data (Oregon State University, Hermiston Research and Education Center, Hermiston, OR; https://www.usbr.gov/pn/agrimet/) hourly weather data that used evapotranspiration and growing degree days plus multiple independent local extended weather forecasts. In addition, soil moisture was monitored with real-time soil moisture sensors. Irrigation was applied once a week. Gas sample collection took place 2 h after irrigation ended and within the 1000 and 1200 h window depending on irrigation scheduling (Parkin and Ventera, 2010). The change in concentration of gases within each chamber was determined by withdrawing 35 mL of air from the headspace every 20 min over an hour period after the cap was placed on the chamber base using 60-mL polypropylene syringes. Gas samples were immediately transferred to an evacuated 12 mL Labco Exetainer (Labco Limited, High Wycombe, Buckinghamshire, UK) vial and taken to the laboratory for determination of CO₂, CH₄ and N₂O by gas chromatography. At the time of gas sampling, chamber temperature and air temperature before and after measurements were recorded using a digital differential thermocouple thermometer (Omega HHM290 Supermeter; Omega Engineering Inc., Stamford, CT). Samples were stored in an incubator at 25°C and analyzed immediately. A Varian CP-3800 GC (Varian, Palo Alto, CA) equipped with a thermal conductivity, flame ionization and electron capture detector was used to measure CO₂, CH₄ and N₂O concentrations.

Fluxes of CO₂, CH₄ and N₂O were calculated from the slope of gas concentration over time, based on chamber temperature, and volume and surface area of the chamber (Parkin and Ventera, 2010). Each sampling was checked for nonlinearity of fluxes according to the protocols outlined by the USDA-ARS GRACE Net. Cumulative fluxes were determined by summing individual flux measurements over the growing season. Time-integrated seasonal fluxes of CO₂, CH₄ and N₂O from each treatment were calculated by averaging the flux between sampling times and multiplying by the interval between sampling dates (Collins et al., 2011). The GHG emission factor of each treatment was expressed as the percentage of the N applied as commercial fertilizer and calculated: N₂O emissions factor = [(N₂O-N_fertilized – N₂O-N TREE only)/N_applied] × 100; where N₂O-N_fertilized is the total N₂O emission of intercrop or monoculture treatments, N₂O-N TREE only is the total N₂O emission from the monoculture tree treatment, and N_applied is the kg N ha⁻¹ applied to the intercrop and monoculture treatments.
Soil samples (0–15 cm depth) were collected at each gas sampling interval within 1 m of each sampling chamber and sieved to pass a 2-mm screen with plant fragments removed. Gravimetric soil moisture content, \( \text{NH}_4^+–\text{N} \) and \( \text{NO}_3^––\text{N} \) concentrations, and pH were determined for each sample. Gravimetric soil moisture of each sample was determined by oven drying at 105°C for 24 h. An estimate of the average field capacity was determined using a volumetric soil–water method described by Hook and Burke (2000). Briefly, air-dried sieved (2 mm) soil was packed lightly into 50-cm\(^3\) graduated cylinders and 5 mL of distilled water was slowly added. The cylinder was covered with perforated parafilm (American National Can, Greenwich, CT) and allowed to equilibrate. After 24 h, soil volume and water content of the wetted front was determined. Mineral N was obtained by extracting 10-g soil subsamples with 1 mol L\(^{-1}\) KCl and analyzed on a QuikChem AE flow-injection analyzer (Lachat Zellweger, Loveland, CO). Soil pH was measured using a 1:2 soil/deionized water solution on a Corning 445 pH Meter (Corning Incorporated, Corning, NY) (Robertson et al., 1999). Soil carbonates were removed from each sample with 0.33 mol L\(^{-1}\) H\(_3\)PO\(_4\) before C analyses (Follett and Pruessner, 2001). Total C concentration of soil samples (25 mg) were determined by dry combustion on an Elementar model Vario EL III CNS Analyzer (Elementar, Hanau, Germany).

**Statistical Analysis**

Averages and standard errors of the mean for soil moisture, \( \text{NO}_3^––\text{N} \), \( \text{NH}_4^+–\text{N} \), and \( \text{CO}_2–\text{C} \), \( \text{CH}_4–\text{C} \), \( \text{N}_2\text{O}–\text{N} \) were determined for each sampling interval. Data from paired chambers within each replicate was averaged. Analysis of Variance was conducted using PROC MIXED GLM of (SAS Institute, 2011). Years and replicates were considered random, while the treatments were considered fixed effects. Means among treatments for soil \( \text{NO}_3^––\text{N} \), \( \text{NH}_4^+–\text{N} \), and \( \text{CO}_2–\text{C} \), \( \text{CH}_4–\text{C} \), \( \text{N}_2\text{O}–\text{N} \) cumulative gas emissions and global warming potentials (GWP) were compared using the Tukey-Kramer significant difference test. All tests for significance were conducted at the \( P \leq 0.05 \) levels (Table 2).

**RESULTS AND DISCUSSION**

**Air and Flux Chamber Temperature, and Soil Water Content**

Average growing season air temperatures were similar among the 2011 through 2014 growing seasons ranging from a low of 10.5°C to a high of 30.4°C with an average annual precipitation of 163 mm (Fig. 1). Soil temperatures averaged 19.2°C for the first half (April–June) of the growing season and 22.9°C for the second half (July–September). The gas flux chamber temperatures were 1 to 2°C higher than the ambient air temperature at the time of sampling (data not shown).

Gravimetric soil moisture contents were above field capacity (FC = 0.11 g g\(^{-1}\)) during much of the growing seasons averaging 0.124, 0.146, and 0.164 g g\(^{-1}\) for the PM, IC, and SM, respectively. Monthly soil moisture of the surface 0- to 15-cm soil layer averaged 0.12 g g\(^{-1}\) from April to May and increased above field capacity from July to September for the PM and IC and significantly greater for the SM (Fig. 3). Increasing summer temperatures and higher evapotranspiration from the
hybrid poplar trees and switchgrass resulted in greater irrigation applications in the later years of the study. Soil moisture was greater in the IC plots than PM or SM which may have resulted from cooler soil temperatures due to tree shading and the soil cover of the intercropped switchgrass that reduced evaporation and/or water demand by the switchgrass. Soil density in 2011 was 1.63 Mg m\(^{-3}\) and increased to 1.93 Mg m\(^{-3}\) in 2014. The increase in soil density resulted from the wheeled equipment used during fertilizing, harvesting, tedding and baling operations.

**Soil NH\(_4^+\)-N and NO\(_3^-\)-N**

Nitrate was the dominant form of inorganic N in the 0- to 15-cm soil layer of each sampling date over the 2011–2014 growing seasons (Fig. 4), representing greater than 90% of the mineral N. Soil mineral N (NH\(_4^+\)-N and NO\(_3^-\)-N) of the non-fertilized PM averaged 4 mg N kg\(^{-1}\) soil during each growing season (Fig. 4). Soil mineral N was significantly higher following fertilization in the spring and summer each year for the IC and SM reaching 80 to 90 mg N kg\(^{-1}\) soil following the July applications in 2013 and 2014. Mineral N of the IC and SM declined to PM levels after 2 wk of application, except in 2013 where mineral N remained elevated for the following 6 wk.

**Greenhouse Gas Emissions: CO\(_2\), CH\(_4\), and N\(_2\)O**

**CO\(_2\)-C Flux rates, Seasonal Emissions and Biomass Production**

Seasonal (167 d) CO\(_2\)-C flux patterns from the PM, IC and SM were similar among years, increasing as soil temperature increased and switchgrass and poplar matured during the growing season (Fig. 5). In 2011, CO\(_2\)-C soil respiration was similar among the PM, IC, and SM with a range of 40 to 70 kg CO\(_2\)-C ha\(^{-1}\) d\(^{-1}\) from July to September, which resulted from the decomposition of the hybrid poplar harvest debris in the establishment year. In subsequent years (2012–2014) average daily CO\(_2\)-C emissions of the IC and SM were higher than the PM. The higher emissions likely resulted from greater microbial activity and root respiration from the switchgrass and hybrid poplar. Although CO\(_2\)-C respiration fluxes were lower for the PM the pattern of emissions over the growing season were similar to the IC and SM. Peak CO\(_2\)-C fluxes occurred during June and July.

Nikiema et al. (2011) and others (Lee et al., 2007; Schmer et al., 2012) reported CO\(_2\) flux rates under fertilized and non-fertilized switchgrass ranged from 15 to 60 kg CO\(_2\)-C ha\(^{-1}\) d\(^{-1}\) and reported N fertilization had no effect on soil respiration rates. Peichl et al. (2006) measured CO\(_2\) flux rates from a poplar (Populus eloides × Populus nigra clone DN-177) intercropped with barley (Hordeum vulgare L.) and a barley monoculture in southern Ontario, Canada. They found soil respiration rates ranged from 72 to 120 kg CO\(_2\)-C ha\(^{-1}\) d\(^{-1}\) in the barley monoculture system and were slightly higher in the poplar intercropping system at rates between 72 to 192 kg CO\(_2\)-C ha\(^{-1}\) d\(^{-1}\). Peichl et al. (2006) also reported annual soil respiration was 3.7 and 2.8 Mg C ha\(^{-1}\) y\(^{-1}\) measured during the growing season (July–October) from the poplar intercropping and barley monoculture cropping systems, respectively. Growing season soil respiration in our study averaged 3.2, 3.9, and 4.0 Mg C ha\(^{-1}\) for the PM, IC, and SM, respectively and was similar to that reported by Peichl et al. (2006).

Annual biomass C of the perennial switchgrass and hybrid poplar increased each year of the study (Table 3). Biomass C of the PM on average tripled each production year; IC biomass doubled after the second production year, where SM production peaked in 2013 then declined. The decline in SM production was not significantly different among years two through four. Cumulative biomass C produced over the 4 yr of cropping was 27.6, 25.5, and 14.4 Mg C ha\(^{-1}\) (65.7, 60.7, and 34.3 Mg DM ha\(^{-1}\)) for the IC, SM, and PM, respectively. The four year cumulative
Table 3. Aboveground biomass-C, soil C and time-integrated growing season CO$_2$–C emissions from the monoculture poplar, poplar/switchgrass intercrop and monoculture switchgrass treatments for the 2011 to 2014 growing seasons.

<table>
<thead>
<tr>
<th>Year</th>
<th>Monoculture poplar</th>
<th>Poplar + switchgrass</th>
<th>Monoculture switchgrass</th>
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<tbody>
<tr>
<td></td>
<td>Mg C ha$^{-1}$</td>
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<td>Mg C ha$^{-1}$</td>
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<td>2011</td>
<td>0.5 Da</td>
<td>0.7 Da</td>
<td>0.68a</td>
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<tr>
<td>2012</td>
<td>1.7Cb</td>
<td>5.9Ca</td>
<td>7.6Aa</td>
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<td>2013</td>
<td>5.8Bb</td>
<td>10.3Ba</td>
<td>9.3Aa</td>
</tr>
<tr>
<td>2014</td>
<td>14.4Ab</td>
<td>19.7Aa</td>
<td>8.0Ac</td>
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<td>Cumulative‡</td>
<td>14.4b</td>
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<td>Soil C sequestered (2011–2014)</td>
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<td>2014</td>
<td>2.9Bb</td>
<td>3.68a</td>
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<td>Cumulative‡</td>
<td>12.9b</td>
<td>15.5a</td>
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<td>Change in C = (dry matter biomass C + Soil C) – (CO$_2$–C)</td>
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<td></td>
<td>Mg C ha$^{-1}$ season$^{-1}$</td>
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<td>2011</td>
<td>-3.7Da</td>
<td>-2.9Da</td>
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<tr>
<td>2012</td>
<td>-1.5Cc</td>
<td>0.9Cb</td>
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<td>2013</td>
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<td>7.0Ba</td>
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<td>Cumulative</td>
<td>1.7b</td>
<td>14.7a</td>
<td></td>
</tr>
</tbody>
</table>

† Means followed by the same uppercase letter within a treatment among years are not significantly different at $P < 0.05$; Means followed by the same lowercase letters among treatments within a year are not significantly different at $P < 0.05$.
‡ Four year cumulative values of the monoculture poplar and poplar/switchgrass intercrop biomass produced are not the sum of biomass measured each year but the total tree biomass produced in 2014 and cumulative switchgrass biomass harvested each year for the intercrop.
§ CO$_2$–C emissions measured over the growing season (167 d, April–September); Negative values indicate CO$_2$ soil respiration exceeded biomass C production.

Values of the PM and IC biomass produced was not the sum of tree biomass measured each year but was derived from the total tree biomass produced by 2014; where the IC includes the cumulative switchgrass biomass harvested each year. The IC and SM produced significantly more biomass than the PM. Collins et al. (2010) and Kimura et al. (2015) reported similar cumulative dry matter and C yields of irrigated switchgrass monocultures over 3 yr on a site located close to the current study on a Quincy soil. Cumulative three-year yields ranged from 34 to 47 Mg DM ha$^{-1}$ (15–20 Mg C ha$^{-1}$) depending on the cultivar. Collins et al. (2010) reported biomass yields of the switchgrass cultivar Kanlow was 3.3 Mg DM ha$^{-1}$ in the establishment year and 47 Mg DM ha$^{-1}$ (20 Mg C ha$^{-1}$) over the three year study which exhibited a similar production track as found in the current study. They also reported profile root biomass of Kanlow produced after three seasons represented 3.3 Mg C ha$^{-1}$ to 1-m depth and that soil C increased 20% in the 0- to 15-cm soil layer. After 4 yr of cropping in the current study soil C increased 0.2, 2.6, and 3.9 Mg C ha$^{-1}$ in the 0- to 15-cm of the PM, IC, and SM, respectively (Table 3).

Tree based intercropping systems are considered to be C sinks because the incorporation of trees within the intercrop allows for greater CO$_2$ sequestration from the atmosphere and subsequently higher C storage (Thevathasan and Gordon, 2004; Evers et al., 2010). Peichl et al. (2006) found that after 13 yr of poplar intercropping the total C pool of above- and belowground components yielded 68.5 and 96.5 Mg C ha$^{-1}$ in a barley monoculture and poplar intercropped system, respectively. They also reported that the total C pool of the poplar intercrop was 41% greater than the monoculture. Gamble et al. (2014) in a two year poplar-switchgrass non-irrigated intercropping study reported switchgrass yields ranged 2.8 to 5.2 Mg DM ha$^{-1}$ (1.2–2.2 Mg C ha$^{-1}$) at two sites in Northern Minnesota. Switchgrass intercropped with pine in the southeastern United States produced 4.1 to 10.3 Mg DM ha$^{-1}$ after 2 yr of cropping (Albaugh et al., 2012; Krapfl et al., 2015; Tian et al., 2015) compared with yields of established monoculture switchgrass stands of 16 to 36 Mg DM ha$^{-1}$ (McLaughlin and Kszos, 2005; Albaugh et al., 2012). Compared with other temperate agroforestry systems, the intercropped switchgrass biomass C found in the present study after 2 yr was 4.2 Mg C ha$^{-1}$ (10 Mg DM ha$^{-1}$) and after 4 yr was 5.3 Mg C ha$^{-1}$ (13 Mg DM ha$^{-1}$) and were 33% less than the switchgrass monoculture (Table 3). The reduction in switchgrass production in the IC was attributed to shading by the hybrid poplar trees (Table 3). The greater yield in IC compared with other intercropping studies was attributed to irrigation and fertilization management.

Total seasonal CO$_2$–C emissions were similar among treatments and exceeded biomass production in 2011 (Table 3). These emissions were attributed to decomposition of hybrid poplar harvest debris since switchgrass and poplar development was minimal. Seasonal CO$_2$–C emissions from the IC, SM, and PM peaked in 2012 then declined and were significantly greater in the IC and SM than PM (Table 3). Negative values indicate CO$_2$–C emissions exceeded biomass C production, where positive values were the sequestering of C. The greatest sequestration of C into biomass occurred in 2014. By the fourth year (2014) biomass C production was 5, 5.5, and 2 times greater than soil CO$_2$–C emissions for the PM, IC, and SM, respectively. Cumulative four year biomass C produced including the C sequestered into the soil of the PM was slightly greater than the four year seasonal CO$_2$–C emissions, where, biomass production for the SM and IC exceeded CO$_2$–C emissions by an average of 14.1 Mg C ha$^{-1}$. The greater C assimilated within the intercrop compensated for higher C losses via soil respiration and other C losses from the system which resulted in a net accumulation of carbon, compared with the PM (Peichl et al., 2006; Nikiema et al., 2011; Schner et al., 2012). There are several things to consider from this interpretation: first, this approach was not an attempt to short circuit accepted methods of determining net ecosystem production (NEP), but to show that the biomass produced over a growing season and the increase in soil organic C significantly offset growing season soil CO$_2$–C fluxes. The defini-
ation of NEP is the difference between the amount of organic C fixed by photosynthesis in an ecosystem and total ecosystem respiration \( R_{ecosyst} \) and represents the organic C available for storage within the system or loss from it by some export process (Woodwell and Whittaker, 1968). Soil respiration \( (S_R) \) has been reported to represent 30 to 60% of total \( R_{ecosyst} \), with an average of 50% depending on the type of ecosystem (Bloemen et al., 2010; Reichstein et al., 2012; Deogu et al., 2013). Randerson et al. (2002) suggested that NEP could equate to \( R_{ecosyst} \) in the ecosystem, where Lovett et al. (2006) contended it was only valid if inputs and outputs of organic C are negligible. Yuste et al. (2005) measured soil respiration in a mixed temperate forest (\( Pinus sylvestris \) L. and \( Quercus robur \) L.) and determined that the ratio of \( S_R/R_{ecosyst} \) ranged from 0.58 to 0.76. Further, they reported that the contribution of \( S_R \) to \( R_{ecosyst} \) varied seasonally with minimum contributions during summer (<50% of \( R_{ecosyst} \)) and maximum contributions during winter (>94% of \( R_{ecosyst} \)). A significant portion of the heterotrophic soil respiration was influenced by the location in the soil profile and by the total organic C content of soils. If the assumption is made that \( S_R \) is 50% of \( R_{ecosyst} \) and that switchgrass root production was similar to that Collins et al. (2010) reported for switchgrass the estimate of \( C \) accumulation would be lower but still positive for the intercropped and switchgrass treatments after 4 yr of production.

Another consideration was that soil \( CO_2-C \) flux was only measured during the growing season. However, sampling during this period represented the major production period of plant biomass, organic \( C \) accumulation and the maximum period of soil respiration. The \( R_{ecosyst} \) would be significantly reduced in the fall and winter months since both switchgrass and poplar enter into dormancy in October and soil respiration rates decrease significantly as soil temperatures decline through fall and winter months. Poplar and switchgrass typically break dormancy in April–May and the sampling covered this period. It is noted that additional measurements made during the winter and early spring would improve the estimates of the effect of intercropping on \( CO_2-C \) emissions.

**CH\(_4\)--C Flux rates and Seasonal Emissions**

Methane (\( CH_4-C \)) fluxes were similar among treatments throughout the growing season (Fig. 6). Daily soil methane uptake rates averaged -0.72, -0.76, and -0.42 g \( CH_4-C \) ha\(^{-1} \) d\(^{-1} \) for the PM, IC, and SM, respectively. Methane uptake varied during the growing season (2011–2014) with highest uptake occurring in the spring (April–June) then declined from July to September. Increasing soil moisture later in the season likely inhibited microbial activity and reduced diffusion (Khalil and Baggs, 2005; Le Mer and Roger, 2001). Following N fertilization after the July harvest methane uptake from the IC and SM soil increased while no effect was observed for the PM. Soil methanotrophic activity (\( CH_4 \) consumption) generally increases to a soil’s field capacity then decreases when soil water content exceeds field capacity and gaseous transfer is reduced. At low water contents (22–60%), methanotrophy is dependent on the level of soil fertility (Khalil and Baggs, 2005; Le Mer and Roger, 2001). After fertilization and increasing soil moisture \( CH_4-C \) exhibited several spikes in emissions from the SM ranging from 0.5 to 1.3 g \( CH_4-C \) ha\(^{-1} \) d\(^{-1} \) over a few weeks after fertilization that reduced \( CH_4-C \) uptake. Methane oxidation has been shown to decline with application of N fertilizers. Le Mer and Roger (2001) reported that urea and \( NH_4 \)-based fertilizers inhibit \( CH_4 \) oxidation where \( NO_3^{-} \)-based fertilizers do not. The inhibition of \( CH_4 \) oxidation in soils by \( NH_4 \) originates from the competition at the level of the methane monoxygenase, leading to a reallocation of the \( CH_4 \) oxidizing activity toward nitrification and the toxicity of \( NO_2 \) that can be produced inhibiting oxidation (Le Mer and Roger, 2001).

Seasonal methane uptake for the PM, IC, and SM was lower than a number of studies have reported in the literature. Methane fluxes reported in the literature from switchgrass production range from -3.8 to 2.4 g \( CH_4-C \) ha\(^{-1} \) d\(^{-1} \) for fertilized monoculture switchgrass and \(-6.8 \text{ to } -3.8 \text{ g } CH_4-C \text{ ha }^{-1} \text{ d }^{-1} \) for unfertilized switchgrass and are predominately sinks for \( CH_4-C \) (Nikiema et al., 2011; Schmer et al., 2012; Wile et al., 2014; Raun et al., 2016). Total growing season soil \( CH_4-C \) uptake was not significantly different among the PM, IC, and SM treatments (Table 4).

**\( N_2O-N \) Flux rates and Seasonal Emissions**

Nitrous oxide fluxes from the PM were similar among the 2011–2014 growing seasons averaging 3.7, 1.3, 1.0, and 2.5 g \( N_2O-N \) ha\(^{-1} \) d\(^{-1} \), respectively (Fig. 7). Data are presented as the daily \( N_2O-N \) flux rates from the PM, IC and SM treatments. \( N_2O-N \) fluxes for the IC and SM showed minimal increases following the spring fertilizer applications with daily fluxes increasing each year after fertilization, averaging 5.0, 8.2 and 14.2 g \( N_2O-N \) ha\(^{-1} \) d\(^{-1} \) for 2012, 2013, and 2014. Major \( N_2O-N \) increases occurred after the second fertilizer application in July with the greatest average monthly fluxes occurring during the 2013 growing season that persisted for up to 5 wk after application. Highest emissions recorded were 240 g \( N_2O-N \) ha\(^{-1} \) d\(^{-1} \) occurring within 3 wk after application in 2013 and 200 g \( N_2O-N \) ha\(^{-1} \) d\(^{-1} \) in

![Fig. 6. Average monthly methane (\( CH_4-C \)) flux rates from the monoculture poplar (PM), poplar/switchgrass intercrop (IC) and monoculture switchgrass (SM) treatments for the 2011 to 2014 crop growing seasons.](image-url)
Soil Science Society of America Journal 2014. N$_2$O-N emissions from the IC and SM declined to background levels comparable to that of the PM by mid-August each year. We attributed the lower N$_2$O-N fluxes to greater aeration of the soil relative to low soil water contents below field capacity. Soil water content is related to water-filled pore space and soil NO$_3$ concentrations are key factors affecting N$_2$O-N emissions (Liu et al., 2007; Snyder et al., 2009; Signor and Cerri, 2013). The soil water contents among the treatments increased later in the growing season and in later years as compaction increased from 1.63 to 1.93 Mg m$^{-3}$ suggesting N$_2$O emissions were generated from denitrification rather than nitrification as water applications increased (Ruser et al., 2006; Buchkina et al., 2013).

Evers et al. (2010) found that high soil water contents correlated with N$_2$O-N emission from summer to spring in both monoculture and hybrid poplar-barley intercropped fields. In the IC soil water was higher, due to a reduction in evaporation from soil as a result of shading, which could enhance denitrification. Evers et al. (2010) reported N$_2$O-N emissions from monoculture and intercropped systems were 3.9 and 2.7 kg ha$^{-1}$, respectively. Schmer et al. (2012) found N$_2$O-N fluxes ranged from 0.24 to 8.6 g N$_2$O-N ha$^{-1}$ d$^{-1}$ for fertilized switchgrass. Raun et al. (2016) in a

### Table 4. Seasonal CH$_4$–C emissions from the monoculture poplar, poplar/switchgrass intercrop and monoculture switchgrass treatments for the 2011-2014 crop years.

<table>
<thead>
<tr>
<th>Cropping Year</th>
<th>Monoculture Poplar</th>
<th>Poplar/switchgrass Intercrop</th>
<th>Monoculture Switchgrass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>April-June</td>
<td>July-September</td>
<td>Growing season†</td>
</tr>
<tr>
<td>2011</td>
<td>−59Aa</td>
<td>−59Aa</td>
<td>−59Aa</td>
</tr>
<tr>
<td>2012</td>
<td>−59Aa</td>
<td>−59Aa</td>
<td>−59Aa</td>
</tr>
<tr>
<td>2013</td>
<td>−59Aa</td>
<td>−59Aa</td>
<td>−59Aa</td>
</tr>
<tr>
<td>2014</td>
<td>−59Aa</td>
<td>−59Aa</td>
<td>−59Aa</td>
</tr>
<tr>
<td>Cumulative</td>
<td>−59Aa</td>
<td>−59Aa</td>
<td>−59Aa</td>
</tr>
</tbody>
</table>

† CH$_4$–C emissions measured over the growing season (167 d, April-September) each year were interpolated linearly between measurements to estimate cumulative flux. Negative values indicate that CO$_2$ emissions exceeded biomass production.

‡ Means followed by the same uppercase letters within a sampling time among years are not significantly different at $P < 0.05$; Means followed by the same lowercase letters among treatment within a sampling time and year among treatments are not significantly different at $P < 0.05$.

§ Compares the values between sampling time 1 (April to June) and time 2 (July to Sep) at $P < 0.05$.

Fig. 7. Nitrous oxide (N$_2$O-N) flux rates from the monoculture poplar (PM), poplar/switchgrass intercrop (IC) and monoculture switchgrass (SM) for the 2011 to 2014 crop growing seasons. Error bars for each date by treatment are standard errors, $n = 8$. 

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study in the upper mid-west reported that average N\textsubscript{2}O emissions ranged from 1.28 g N ha\textsuperscript{-1} d\textsuperscript{-1} in unfertilized switchgrass to 25.8 g N ha\textsuperscript{-1} d\textsuperscript{-1} in fertilized switchgrass. They also reported that the maximum daily N\textsubscript{2}O emission was 270 g N ha\textsuperscript{-1} d\textsuperscript{-1} in fertilized switchgrass which was similar to that found in the present study.

Cumulative growing season N\textsubscript{2}O-N emissions from the PM averaged 241 g N\textsubscript{2}O-N ha\textsuperscript{-1} over 2011 to 2014 with a low of 113 g N\textsubscript{2}O-N ha\textsuperscript{-1} in 2013 (Table 5). Seasonal emissions from the fertilized IC and SM increased significantly each year for the IC and SM due to switchgrass. Also reported that the maximum daily N\textsubscript{2}O emission was 270 g N ha\textsuperscript{-1} d\textsuperscript{-1} in fertilized switchgrass which was similar to that found in the present study.

Cumulative growing season N\textsubscript{2}O-N emissions from the PM averaged 241 g N\textsubscript{2}O-N ha\textsuperscript{-1} over 2011 to 2014 with a low of 113 g N\textsubscript{2}O-N ha\textsuperscript{-1} in 2013 (Table 5). Seasonal emissions from the fertilized IC and SM increased significantly each year for the IC and SM due to switchgrass. Also reported that the maximum daily N\textsubscript{2}O emission was 270 g N ha\textsuperscript{-1} d\textsuperscript{-1} in fertilized switchgrass which was similar to that found in the present study.

Table 5. Seasonal N\textsubscript{2}O-N flux and emissions factors for the monoculture poplar, poplar/switchgrass intercrop and monoculture switchgrass treatments for the 2011 to 2014 crop years.

<table>
<thead>
<tr>
<th>Cropping year</th>
<th>April-June</th>
<th>July-September</th>
<th>Growing season†</th>
<th>July-September</th>
<th>Growing season</th>
<th>April-June</th>
<th>July-September</th>
<th>Growing season</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td>–</td>
<td>280Aa</td>
<td>–</td>
<td>249Bb</td>
<td>249Ca</td>
<td>–</td>
<td>264Ba</td>
<td>264Ca</td>
</tr>
<tr>
<td>2012</td>
<td>141BAa†</td>
<td>99Bb</td>
<td>240ABb</td>
<td>165Ba‡</td>
<td>449Ba</td>
<td>615BaCa</td>
<td>142Ba‡</td>
<td>657Ba</td>
</tr>
<tr>
<td>2013</td>
<td>518Aa</td>
<td>62Bb</td>
<td>113Bb</td>
<td>111Ba§</td>
<td>1825Aa</td>
<td>1936Aa</td>
<td>123Ba‡</td>
<td>2731Aa</td>
</tr>
<tr>
<td>2014</td>
<td>168Ab</td>
<td>163Ab</td>
<td>331Ab</td>
<td>875Aa</td>
<td>809Ba</td>
<td>1685ABa</td>
<td>522Ab</td>
<td>878Ba</td>
</tr>
<tr>
<td>Cumulative</td>
<td>360b</td>
<td>603b</td>
<td>963b</td>
<td>1151a§</td>
<td>3333a</td>
<td>4485a</td>
<td>787ab §</td>
<td>5263a</td>
</tr>
<tr>
<td>Average</td>
<td>120b</td>
<td>151b</td>
<td>241b</td>
<td>384a§</td>
<td>833a</td>
<td>1121a</td>
<td>262b</td>
<td>1316a</td>
</tr>
</tbody>
</table>

† N\textsubscript{2}O-N emissions measured over the growing season (167 d, April–September) each year were interpolated linearly between measurements to estimate cumulative flux.
‡ Means followed by the same uppercase letters within a sampling time between years are not significantly different at \(P < 0.05\); Means followed by the same lowercase letters within a sampling time and year among treatments are not significantly different at \(P < 0.05\).
§ Compares the values between sampling time 1 (April to June) and time 2 (July to September) within a year and treatment at \(P < 0.05\).

Global Warming Potentials (GWP)

Greenhouse gas emissions were estimated over the growing season each year and interpolated linearly between measurements to estimate cumulative greenhouse gas losses and GWP of greenhouse gasses, relative to CO\textsubscript{2}. Seasonal N\textsubscript{2}O GWP of the PM was similar among years averaging 114 kg CO\textsubscript{2eq} ha\textsuperscript{-1} compared with significant increases each year for the IC and SM due to switchgrass fertilization (Table 6). The Quincy soil was a sink for CH\textsubscript{4} with an average uptake of 3.3 kg CO\textsubscript{2eq} ha\textsuperscript{-1} among all systems. The cumulative four year seasonal GWP based on CH\textsubscript{4} and N\textsubscript{2}O for the PM averaged 2610 kg CO\textsubscript{2eq} ha\textsuperscript{-1} for the IC and SM where N fertilization of the monoculture switchgrass study in the Northern Great Plains as 0.25%. Wile et al. (2014) reported that cumulative seasonal (May–November) N\textsubscript{2}O emissions from monoculture switchgrass stands were <1 kg N\textsubscript{2}O-N ha\textsuperscript{-1} an NEF of 0.8% with highest emissions released from switchgrass fertilized with 120 kg N ha\textsuperscript{-1}. McGowan (2015) found fertilizer induced emission factors of switchgrass increased from 0.7% at 50 kg N ha\textsuperscript{-1} to 2.6% at 150 kg N ha\textsuperscript{-1}, demonstrating a nonlinear increase in N\textsubscript{2}O emissions from fertilized switchgrass.

GWP = \(\frac{N\textsubscript{2}O}{CO\textsubscript{2}} + \frac{CH\textsubscript{4}}{CO\textsubscript{2}}\textsuperscript{eq} + \frac{N\textsubscript{2}O}{CO\textsubscript{2}}\textsuperscript{eq}\) – (aboveground biomass CO\textsubscript{2eq}).

Positive values indicated the system was emitting CO\textsubscript{2eq} from the atmosphere, negative values sequestering CO\textsubscript{2eq} from the atmosphere. GWP\textsubscript{Net} in 2011 among all systems averaged
+12.1 Mg CO$_2$eq ha$^{-1}$. As discussed earlier CO$_2$ emissions exceeded biomass C in the first 2 yr of the PM and first year of the IC and SM treatments resulting from decomposition of previous poplar harvest debris. The contributions of CO$_2$eq emissions from soil to GWP were offset each successive year by the C fixed in the crop biomass with the hybrid poplar sequestering more atmospheric CO$_2$eq than switchgrass biomass. By year four of the study, the GWP Net of PM (−42.1 Mg CO$_2$eq ha$^{-1}$) and IC (−57.9 Mg CO$_2$eq ha$^{-1}$) showed a significantly greater sink for atmospheric CO$_2$ sequestered by the poplar biomass than the SM (−13.7 Mg CO$_2$eq ha$^{-1}$).

The four year cumulative net GWP values of the PM and IC biomass produced was the total tree biomass produced in 2014 and cumulative switchgrass biomass harvested each year for the intercrop. Cumulative 4 yr biomass C produced in the PM closely matched the 4 yr CO$_2$–C emissions (1.7 Mg C ha$^{-1}$), where biomass production for the SM and IC exceeded CO$_2$–C emissions averaging 14.1 Mg C ha$^{-1}$. CH$_4$–C uptake was not significantly different between treatments, while GS N$_2$O–N emissions for PM were ~80% lower than both IC and SM. N$_2$O emissions factors averaged 0.7% of the applied N-fertilizer. Cumulative contributions of CO$_2$eq emissions to GWP were offset by the C fixed in the aboveground biomass resulting in a net GWP zero balance for the PM after 4 yr, where, IC and SM sequestered significantly more atmospheric CO$_2$ to yield a net GWP of −42 and -32 Mg CO$_2$eq ha$^{-1}$, respectively.

**SUMMARY**

Highly productive, commercial hybrid poplar plantations are being managed in the Pacific Northwest for high-value timber production at relatively low stocking densities under irrigation. The open understory was used to produce switchgrass biomass prior to canopy closure in an intercropping system. Intercropping hybrid poplar with switchgrass was found to be a viable alternative to biomass production for bioenergy production than solely in monoculture. The resulting increase in biomass production was found to offset increases in GHGs and GWP resulting from irrigation and fertilization.

Cumulative 4 yr biomass C produced in the PM closely matched the 4 yr CO$_2$–C emissions (1.7 Mg C ha$^{-1}$), where biomass production for the SM and IC exceeded CO$_2$–C emissions averaging 14.1 Mg C ha$^{-1}$. CH$_4$–C uptake was not significantly different between treatments, while GS N$_2$O–N emissions for PM were ~80% lower than both IC and SM. N$_2$O emissions factors averaged 0.7% of the applied N-fertilizer. Cumulative contributions of CO$_2$eq emissions to GWP were offset by the C fixed in the aboveground biomass resulting in a net GWP zero balance for the PM after 4 yr, where, IC and SM sequestered significantly more atmospheric CO$_2$ to yield a net GWP of −42 and -32 Mg CO$_2$eq ha$^{-1}$, respectively.

**Table 6. Net global warming potentials (GWP) for the 2011 to 2014 growing seasons of the monoculture poplar, poplar/switchgrass intercrop and monoculture switchgrass treatments.**

<table>
<thead>
<tr>
<th></th>
<th>Biomass C production</th>
<th>Carbon dioxide</th>
<th>Nitrous oxide</th>
<th>Methane</th>
<th>Net GWP†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Monoculture poplar</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>1.8Da‡</td>
<td>15.5Aa</td>
<td>0.136Aa</td>
<td>-0.0027Aa</td>
<td>+13.8Aa</td>
</tr>
<tr>
<td>2012</td>
<td>6.1Cb</td>
<td>11.8Bb</td>
<td>0.113ABb</td>
<td>-0.0037Aa</td>
<td>+5.8Aa</td>
</tr>
<tr>
<td>2013</td>
<td>21.3Bb</td>
<td>9.5Bb</td>
<td>0.053Bb</td>
<td>-0.0023Aa</td>
<td>-11.8Bb</td>
</tr>
<tr>
<td>2014</td>
<td>52.9Ab</td>
<td>10.7Bb</td>
<td>0.155Ab</td>
<td>-0.0043Aa</td>
<td>-42.1Cb</td>
</tr>
<tr>
<td>Average</td>
<td>11.9b</td>
<td>11.9b</td>
<td>0.114b</td>
<td>-0.0033a</td>
<td></td>
</tr>
<tr>
<td>Cumulative§</td>
<td>52.9b</td>
<td>47.4b</td>
<td>0.457b</td>
<td>-0.0130a</td>
<td>-5.1a</td>
</tr>
<tr>
<td><strong>Poplar/switchgrass intercrop</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>2.4Da</td>
<td>12.7Ba</td>
<td>0.122Ca</td>
<td>-0.0027Aa</td>
<td>+10.4Aa</td>
</tr>
<tr>
<td>2012</td>
<td>21.5Ca</td>
<td>18.4Aa</td>
<td>0.288BCa</td>
<td>-0.0026Aa</td>
<td>-2.88ab</td>
</tr>
<tr>
<td>2013</td>
<td>37.7Ba</td>
<td>12.1Bab</td>
<td>0.907Aa</td>
<td>-0.0020Aa</td>
<td>-24.7Cc</td>
</tr>
<tr>
<td>2014</td>
<td>72.1Aa</td>
<td>13.4Bb</td>
<td>0.789BAb</td>
<td>-0.0043Aa</td>
<td>-57.9Dc</td>
</tr>
<tr>
<td>Average</td>
<td>14.2a</td>
<td>96.6a</td>
<td>0.527a</td>
<td>-0.0029a</td>
<td></td>
</tr>
<tr>
<td>Cumulative§</td>
<td>101.2a</td>
<td>56.6a</td>
<td>2.106a</td>
<td>-0.0116a</td>
<td>-42.5c</td>
</tr>
<tr>
<td><strong>Monoculture switchgrass</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2011</td>
<td>2.1Ba</td>
<td>14.2Aa</td>
<td>0.129Ca</td>
<td>-0.0023Aa</td>
<td>+12.2Aa</td>
</tr>
<tr>
<td>2012</td>
<td>27.8Aa</td>
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<td>0.374BCa</td>
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<td>-11.7Bb</td>
</tr>
<tr>
<td>2013</td>
<td>34.2Aa</td>
<td>14.0Aa</td>
<td>1.261Aa</td>
<td>-0.0028Aa</td>
<td>-18.9Bb</td>
</tr>
<tr>
<td>2014</td>
<td>29.2Ac</td>
<td>14.6Aa</td>
<td>0.855BAb</td>
<td>-0.0020Aa</td>
<td>-13.7Bb</td>
</tr>
<tr>
<td>Average</td>
<td>14.6a</td>
<td>95.6a</td>
<td>0.655a</td>
<td>-0.0026a</td>
<td></td>
</tr>
<tr>
<td>Cumulative§</td>
<td>93.3a</td>
<td>58.5a</td>
<td>2.619a</td>
<td>-0.0104a</td>
<td>-32.2b</td>
</tr>
</tbody>
</table>

† Net GWP = (Soil CO$_2$eq + N$_2$O–CO$_2$eq + CH$_4$–CO$_2$eq) – (aboveground biomass CO$_2$eq), Positive values indicate the system is emitting CO$_2$eq to the atmosphere, negative values sequestering CO$_2$eq from the atmosphere.

‡ Means followed by the same uppercase letters within a treatment among years are not significantly different at P < 0.05; Means followed by the same lowercase letters among treatments within a year, the average or cumulative values are not significantly different at P < 0.05.

§ Four year cumulative value of the monoculture poplar and poplar/switchgrass intercrop biomass produced is not the sum of biomass measured each year but uses the total tree biomass produced in 2014 and cumulative switchgrass biomass harvested each year for the intercrop.
Continued research on the effects of irrigated bioenergy production and the effects of irrigation water applied on GHG emissions in intercropped systems is needed. A suggestion from our observations for future irrigated intercropping hybrid poplar-switchgrass production is to closely match the irrigation needs of each crop. We estimated that the switchgrass within intercropping received 127% more water than needed for production. The over application of irrigation water resulted in increasing soil compaction from management operations and increased soil moisture leading to higher N₂O-N fluxes and reduced CH₄-C oxidation. We suggest a separate irrigation strategy using drip irrigation for hybrid poplar and sprinkler for switchgrass with conversion of switchgrass to drip in later years. Knowledge of the processes regulating GHG emissions from irrigated biomass production will become increasingly important as agricultural water use, water availability and quality are challenged by climate change.

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REFERENCES


