Spatial Modeling of Critical Planting Date for Winter Rye Cover Crop to Enhance Nutrient Recovery

Ali Farsad,* Timothy O. Randhir, Stephen J. Herbert, and Masoud Hashemi

ABSTRACT

Time of planting plays a critical role in nutrient recovery from soils by a winter rye (*Secale cereale* L.) cover crop. A delay in planting can significantly decrease cover crop performance. This study evaluated cover crop planting dates for different areas of Massachusetts using a spatial model based on growing degree days. Field studies were conducted during 2004 through 2009 to estimate biomass production and nutrient recovery of rye under various planting dates from mid-August to early October. A spatial model identified the critical planting date (CPD) for all locations in Massachusetts based on field studies combined with long-term weather data collected from 14 weather stations. In eastern areas of Massachusetts (Zone 5), CPD is the third week of September. In this region, there is adequate time for planting winter rye after corn (*Zea mays* L.) is harvested. Critical planting dates for central parts of the state (Zones 3 and 4) are from the first to second weeks of September. Growers in these regions should consider alternative management strategies including selection of shorter season corn hybrids to meet the suggested cover crop planting dates. The suggested critical planting dates (third–fourth week of August) for northwest regions of Massachusetts (Zones 1 and 2) may not be practical because corn silage is usually not ready for harvest until mid-September. The model can be a powerful decision-making tool for researchers and farmers, not only for winter rye in Massachusetts, but it also can be adapted for use with other cover crop species and for use in other regions where cover crops are grown.

Nonpoint sources of pollution continue to be a major threat to water resources of which N, especially in the form of NO_3–N, is a major issue in agricultural landscapes (Burkart and Stoner, 2001; Sauer et al., 2001; Gulis et al., 2002). Commercial and residential fertilizer use, human and animal wastes, landfills, and industries are the major sources of N pollution (Vidal et al., 2000). Almost 50% of N pollution is related to agricultural activities (Hansen et al., 2000; Owens et al., 2000; Sogbedji et al., 2000). Contamination of water resources can intensify the eutrophication of water bodies, alter the natural conditions of lakes and rivers (Yeomans et al., 1992), and endanger the health of humans and animals (Shirley et al., 1974; Owens et al., 2000; Townsend et al., 2003).

Due to its mobility, N can reach the groundwater through infiltration (leaching) and affect drinking water supplies. The interval between harvesting corn silage in the fall and planting the succeeding spring crop is a critical water recharge period when soil NO_3 is highly susceptible to leaching. This is especially the case when no crop is present to take up N and when considerable amounts of rainfall are received during this period (Watts and Martin, 1981; Keeney and Follett, 1991; Martin et al., 1994). Our previous studies indicated that a significant amount of N can be released into the soil through the mineralization of previously applied manure and plant residues due to warm weather in September and early October and the activity of microorganisms (data not shown). Furthermore, in the U.S. Northeast, most dairy farmers must apply manure to the fields after harvesting silage corn due to a limited manure storage capacity. Winter rye, when used as a cover crop, can play a key role in recovering the residual soil and manure N in the fall and in reducing post-harvest leaching (Staver and Brinsfield, 1998; Vaughan and Evanylo, 1999; Kessavalou and Walters, 1999; Strock et al., 2004). If planted on time, a winter rye cover crop can accumulate as much as 100 kg N ha^{-1} or more, depending on the amount of biomass yield, the residual N present, and other soil properties. This N, which otherwise would have been lost to the environment, is held in the cover crop biomass and becomes available to crops in future seasons (Kessavalou and Walters, 1999; Strock et al., 2004; Herbert et al., 2007;). Therefore, the recovery of N by a winter rye cover crop, along with a manure application in the spring before corn is planted, could supply sufficient N for maximizing yield either without or with a limited amount of fertilizer N.

The time of cover crop planting is a critical factor to maximize N accumulation. A delay in planting the winter cover crop can result in a dramatic reduction in N accumulation and thereby allow higher N loss through leaching. It is not always possible to plant winter rye early in the fall, however, due to practical limitations such as timing of the corn harvest, fall manure application, weather conditions, and other dairy

A. Farsad, Dep. of Plant, Soil and Insect Sciences, Univ. of Massachusetts, Bowditch Hall 107A, 201 Natural Resources Road, Amherst, MA 01003; T.O. Randhir, Dep. of Environmental Conservation, Univ. of Massachusetts, Holdsworth 320, 160 Holdsworth Way, Amherst, MA 01003; S.J. Herbert, Dep. of Plant, Soil and Insect Sciences, Univ. of Massachusetts, Stockbridge Hall 112, 80 Campus Center Way, Amherst, MA 01003; and M, Hashemi, Dep. of Plant, Soil and Insect Sciences, Univ. of Massachusetts, Bowditch Hall 208, 201 Natural Resources Road, Amherst, MA 01003. Received 15 Oct. 2010. *Corresponding author (afarsad@psis.umass.edu).

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Abbreviations: CAG, critical accumulated growing degree days; CPD, critical planting date; CPZ, critical planting zone; GDD, growing degree days; GIS, geographic information system.

Table 1. Winter rye cover crop planting dates in each year of the experiment.

Planting no.	2004	2005	2006	2008	2009
1	18 Aug.	19 Aug.	1 Sept.	5 Sept.	1 Sept.
2	2 Sept.	2 Sept.	8 Sept.	12 Sept.	8 Sept.
3	15 Sept.	16 Sept.	15 Sept.	20 Sept.	14 Sept.
4	29 Sept.	30 Sept.	22 Sept.	29 Sept.	21 Sept.
5	10 Oct.	14 Oct.	29 Sept.	6 Oct.	29 Sept.
6	27 Oct.	28 Oct.	6 Oct.		

Table 2. Average moisture and nutrient content for manure applied during the field experiments.

Manure content	Fraction	Nutrient value	Nutrients applied
	%	g L^{-1}	kg ha^{-1}
Moisture	89.63		
Total N	0.22	2.29	96.2
NH_4–N	0.12	1.25	52.5
Organic N	0.10	1.04	43.7
P as P_2O_5	0.13	1.35	56.7
K as K_2O	0.27	2.82	118.4

farming activities. Therefore, it is important for farmers to know the CPD of the rye cover crop at a site-specific level. We define the CPD as the latest planting date possible that allows maximum potential N accumulation.

To evaluate site-specific CPDs, a geographic information system (GIS) is useful in modeling spatial the variation in growing degree days (GDD) and biomass production. The GIS is a powerful tool that has been widely used in the agricultural sciences for spatial analysis and decision making, especially in locating corn stover collection sites (Haddad and Anderson, 2008), locating animal waste areas (Basnet et al., 2002), identifying agronomically homogeneous areas (Gardi, 2001), and assessing tillage effects on soil compaction (Wiatrak et al., 2009).

In this study, we used GIS and field methods to develop a spatial model for determining the CPDs for winter rye cover crops for farming locations throughout the Commonwealth of Massachusetts. This model can be used as a decision-making tool for researchers, policymakers, and farmers to identify planting regimes that maximize N recovery and minimize its negative impacts on water quality. The specific objectives of this project were: (i) modeling the site-specific CPD for planting of a winter rye cover crop in Massachusetts; (ii) estimating the amount of biomass, N recovery, and economic loss related to delays in planting of cover crop; and (iii) identifying optimal decisions to plant a rye winter cover crop in different locations in Massachusetts.

MATERIALS AND METHODS

Field Experiments

Five field experiments with different seeding dates of rye (Table 1) within a corn–winter rye cropping system were conducted at the Crops and Animal Research and Education Center Farm of the University of Massachusetts in Deerfield, MA, from 2004 to 2009. Planting dates for cover crops each year were optimized based on the results of the previous years. The soil type is a Hadley fine sandy loam (a coarse-silty, mixed, superactive, nonacid, mesic Typic Udifluvent).

Each year, the same cultural practices were followed. Conventional tillage including moldboard plowing and disking were used. Each year, plots (6.9 by 12 m) received 36 kg N ha^{-1}, 16 kg P_2O_5 ha^{-1}, and 13 kg K_2O ha^{-1} before corn was planted. Except in some years, dairy (*Bos taurus*) manure was applied uniformly at the rate of 42,000 L ha^{-1} in the spring before the corn was planted and immediately incorporated into the soil by disking. The nutrient content of the manure is presented in Table 2. Corn was planted in early May in the plots. Weeds were controlled by applying preemergence 4.68 L ha^{-1} of Bicep (atrazine [6-chloro-*N*-ethyl-*N*'-(1-methylethyl)-1,3,5-triazine-2,4,-diamine] + metolachlor [2-chloro-*N*-(2-ethyl-6-methylphenyl)-*N*-(2-methoxy-1-methylethyl)acetamide]; Syngenta, Basel, Switzerland). The presidedress soil NO_3 test (PSNT) (Magdoff et al., 1990) was performed when corn plants were 25 to 30 cm (10–12 inches) high. Sidedress N fertilizer was applied according to the PSNT results. No irrigation was used because it is not a common practice in Massachusetts due to adequate rain during the growing season. Corn was harvested as silage in late August.

The rye cover crop seeds were spread by hand at a rate of 112 kg ha^{-1}. After the seeds were spread, the soil surface was disturbed by a garden weasel to incorporate the seeds into the soil. After seeding, 112 kg N ha^{-1} as Ca–NH_4NO_3 was applied to the rye cover crop at each date to simulate a fall application of manure. Spreading manure on multiple dates on field plots and then incorporating the manure before seeding the rye was not practical.

Tissue samples were collected starting approximately 2 wk after seeding and every 2 wk thereafter (depending on weather conditions). Samples were collected using a 0.1-m^2 quadrate. Three quadrats of cover crop plants cut with shears approximately 1 cm above the soil were randomly harvested on each sampling date at a 0.5-m distance from the previous sampling sites. The samples were dried in a forced-air oven at 80°C for 36 h. The dried samples were weighed and ground fine to pass through a 0.42-mm screen. The samples were analyzed for total N using standard QuikChem methods (Lachat QuikChem 8000 FIA, Zellweger Analytical, Milwaukee, WI).

The experimental design used each year was a randomized complete block design with four replications. Standard statistical analysis was performed for the data using SAS, Version 9.1 (SAS Institute, Cary, NC). Means were compared using the LSD test.

Spatial Model of Growing Degree Days

All field data were standardized to GDD for comparison among years and for planting date recommendations. Weather data were collected onsite with a weather station (WatchDog Model 2700, Spectrum Technologies, Plainfield, IL) and from the NOAA National Climate Data Center website for all years of the study (2004–2009) for the Deerfield location. For each day following planting, the GDD were calculated using

$$g_{\mathrm{d}} = \frac{t_{\max} + t_{\min}}{2} - t_{\mathrm{base}}, \quad g_{\mathrm{d}} \geq 0 \qquad [1]$$

where g_d is daily GDD, t_{max} is the maximum temperature of the day (°C), t_{min} is the minimum temperature of the day (°C), and t_{base} is the base temperature for winter rye (0°C as observed by Stoskopf, 1985). The total accumulated GDD from the planting date to each sampling date were calculated and a regression model was fitted to describe rye dry weight accumulation as a function of GDD (Fig. 1). We used biomass data and cover crop tissue total N collected for several years to develop a

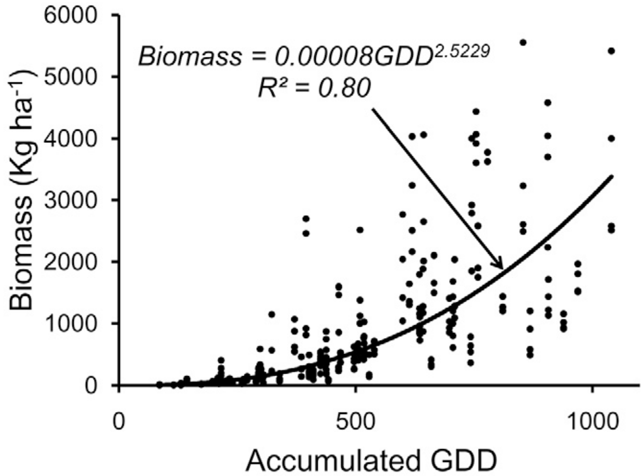

Fig. 1. Scatterplot and functional fit for rye biomass response to accumulated growing degree days (GDD) using experimental data from 2004 to 2009 from Deerfield, MA. For each data point, the accumulated GDD was calculated from planting date to the corresponding sampling date.

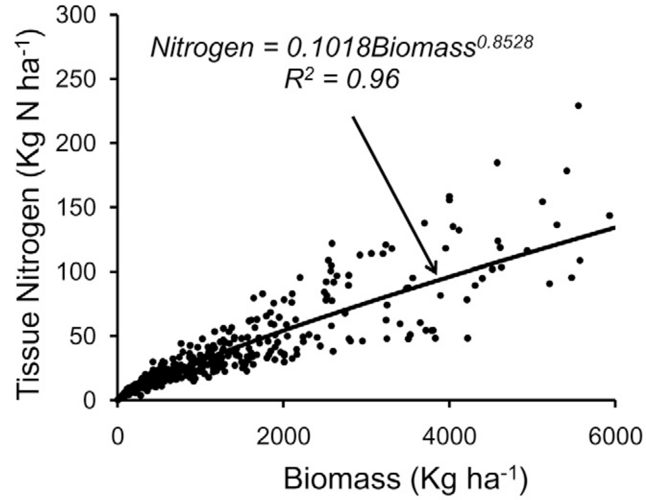

Fig. 2. The relationship determined between tissue total N and biomass production for a rye cover crop using experimental data from 2004 to 2009 from Deerfield, MA.

model that estimates tissue total N (N accumulation) based on biomass production (Fig. 2).

Herbert et al. (2007) suggested that planting rye earlier than 1 September has no significant contribution to additional N uptake in Deerfield, MA. Therefore, we assumed that the CPD for a winter rye cover crop in Deerfield was 1 September.

To establish a baseline for determining the CPD for all locations in the state, the CPD unit was converted from date to GDD by calculating the total sum of daily GDD from 1 September to 31 December. This value is called the critical accumulated GDD (CAG), which is the minimum amount of accumulated GDD required for maximum potential N uptake by the rye cover crop. One reason for calculating the CAG from the planting date to the end of the year rather than to the rye kill date in the spring is that rye biomass production in the spring has no significant contribution to N uptake (Herbert et al., 2007). Because daily GDD may change by year, we used 10-yr daily temperatures of the experimental site for calculating averages of daily GDD. For each arbitrary date of planting, the accumulated GDD can be calculated using the following equation:

$$g=\sum_{d=p}^{e}G_d = \sum_{d=p}^{e}\left(\frac{1}{2}\frac{\sum_{y=y_1}^{y_2} t_{\max_{d,y}}}{y_2-y_1}+\frac{\sum_{y=y_1}^{y_2} t_{\min_{d,y}}}{y_2-y_1}\right)-t_{\text{base}}, \qquad G_d \geq 0 \quad [2]$$

where g is accumulated GDD from the planting date p (1 September for calculating the CAG) to the end of the year (e), G_d is the average GDD of Day d of the year, y_1 is the first year of the averaging period (in this case 1998), y_2 is the last year of the averaging period (in this case 2008), and y is the year index.

Estimating Critical Planting Date for All Locations in Massachusetts

Because the accuracy of a planting date recommendation for a specific day does not seem realistic, week-based recommendations were made. The GDD accumulation for each week beginning 1 August, which is the earliest potential planting date for a rye cover crop in Massachusetts, was calculated using Eq. [2].

Growing Degree Day–Week Raster Maps and Critical Planting Zones

Ten years of weather data from 14 climatic weather stations within and around Massachusetts were downloaded from the National Climate Data Center online databases. A spreadsheet file was created containing values of weekly accumulated GDD from the first week of August to the fourth week of December for all weather stations and then imported into ArcGIS software (ESRI, Redlands, CA). For each weather station, latitude and longitude coordinates were used to digitize the weather station sites. A raster (spatial representation in GIS) map of GDD information was created for each week of cover crop planting window (20 raster maps) for the entire state.

The spline tool was used for interpolating data from the weather stations. This allowed the creation of each week's raster that contained accumulated GDD data from that week to the end of the year. Areas of the state for each raster-week that possessed GDD values closest to the CAG were then selected. We called these areas critical planting zones (CPZs). A mathematical description of the expression used in the spatial analysis of a raster's CPZ, using the raster calculator tool, is

$$z_r=\sum_{i=s}^{k}z_i = \sum_{i=s}^{k}\left[\left(r_i<g_{\text{h}}\right)\text{and}\left(r_{i-1}\geq g_{\text{h}}\right)\right]r_i \quad [3]$$

where r_i is the GDD raster map of the ith week, s is the number of the first GDD-week raster layer containing a CPZ (in this case, the third week of August or 35th week of the year), k is the number of the last GDD map containing a CPZ (in this case, the

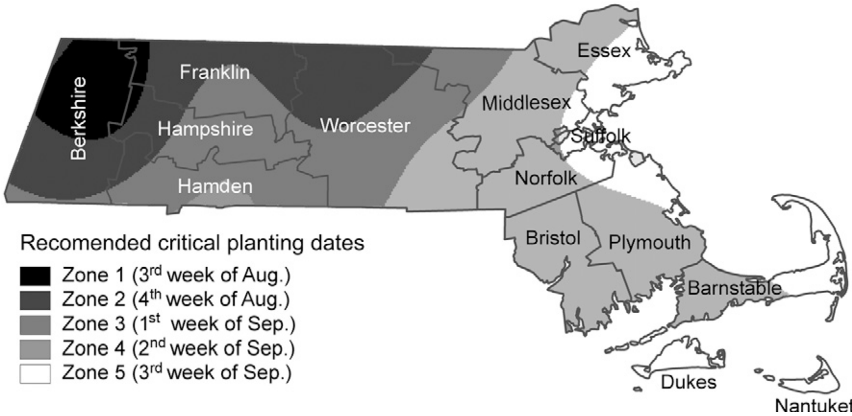

Fig. 3. Critical planting zones for a winter rye cover crop in Massachusetts. The model-recommended planting date is different for each zone and is based on its temperature (growing degree days) regime.

last layer is the third week of September or the 39th week of the year), z_i is a raster map containing the ith CPZ, g_h is the upper limit of the critical GDD range (explained more below), and z_r is a raster containing all the CPZs (Fig. 3). The amount of GDD loss due to each week's delay from the CPD was calculated as

$$P_{g_i} = \sum_{j=1}^{n}\left(\Delta P_{i+j+m-1}\right) \qquad [4]$$

where i represents the delay in planting the cover crop (wk), P_g is a layer containing GDD data for the i weeks' delay in planting the cover crop for all CPZs, P is a GDD-week raster map, m is the first week that contains a CPZ (in this case, the third week of August or 35th week of the year), n is the number of the weeks containing a CPZ, and Δ is a normalizing factor that can have a value of 1 for all pixels in a z_i raster (Eq. [3]) and 0 for others.

Dairy Farm Survey

To test the feasibility of our CPD recommendations, a GIS layer map was created using the spatial data from a survey of dairy farms conducted by Hashemi et al. (2007). For each CPZ, the corn planting date, corn harvesting date, and rye cover crop planting date were extracted from the survey. This information was used to compare the current cover crop planting date for a CPZ with the CPD suggested by the model (Fig. 4).

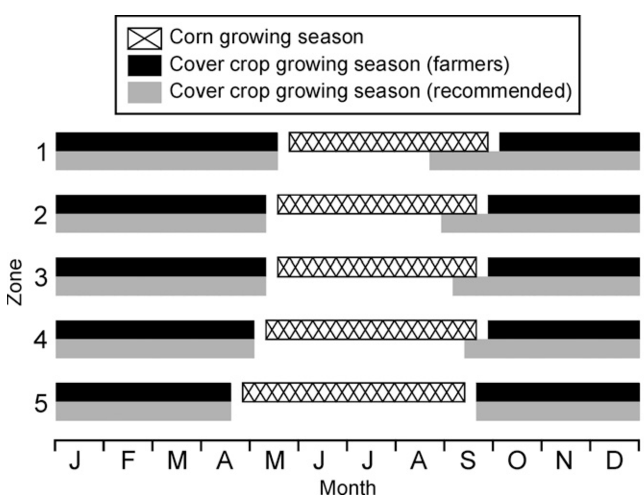

Fig. 4. The corn–rye cropping system identified for the five Massachusetts critical planting zones. There is an overlap between the corn and recommended cover crop growing seasons in Zones 1 to 4, which suggests the need for a change in current management practices.

RESULTS AND DISCUSSION

Biomass production compared with GDD accumulation was derived from the multiyear (2004–2009) data set (Fig. 1). This power function response indicated that relatively small reductions in GDD could have a dramatic negative impact on crop biomass accumulation. A statistical model was also fitted for estimating the N accumulation from biomass production (Fig. 2). A power function indicated a strong correlation between the two traits ($R^2 = 0.96$).

Using Eq. [2], the CAG (with a 1 September seeding date) was calculated from the 10-yr average of daily GDD as 1032 GDD for Deerfield, MA. To determine the CPD for all locations in the state, areas having a GDD value closest to 1032 (CAG) needed to be extracted from each GDD-week raster map. There were few areas found in each week-map with the exact GDD value of 1032, however, so a GDD range between 950 and 1100 was used. This was called critical GDD range.

The negative impact on biomass production, total N uptake, and hence economics caused by a delay in cover crop planting is shown in Table 3. For example, a 1-wk delay in planting the rye cover crop can reduce N accumulation by 27%. The amount of reduction intensified to 49, 66, and 78% for 2-, 3-, and 4-wk delays, respectively, in planting the cover crop. To maximize N recovery, it is important to plant the rye cover crop using the recommended CPD.

Table 3. Average growing degree day (GDD) accumulation, biomass production, N uptake, and economic saving across Massachusetts related to planting at the critical planting date and planting with up to 4 wk delay from the critical planting date.

Parameter	No delay	1 wk delay	2 wk delay	3 wk delay	4 wk delay
Accumulated GDD	1040	908	784	666	560
GDD loss, %	0	13	25	36	46
Biomass, kg ha^{-1}	3284	2334	1609	1068	691
Biomass loss, %	0	29	51	69	79
N accumulation, kg ha^{-1}	106	79	57	40	28
N loss, kg ha^{-1}	0	27	49	66	78
N loss, %	0	25	46	62	74
Value†, US$ ha^{-1}	122	91	66	46	32
Value loss, US$ ha^{-1}	0	31	56	75	90
Value loss, %	0	25	46	62	74

† Based on US$1.15 kg^{-1} N accumulated fertilizer equivalent.

Management Strategies in Each Critical Planting Zone

Providing information to farmers about the economic loss and water quality impairment related to delays in planting the cover crop can play a key role in sustaining agriculture in Massachusetts. Perhaps the most challenging factor for the timely planting of the rye cover crop is the corn harvest date, which, in turn, depends on the corn hybrid maturity and the corn planting date. Because the accumulated GDD is similar for all locations in a specific CPZ, any variations in corn planting dates among farms located in a CPZ should be attributed to the individual grower's management strategy. For example, the current corn planting date in Zone 2 is from early May to early June (Fig. 4). It is quite possible for a farmer to plant corn in early May in this zone, which will enable the establishment of a more effective cover crop system for optimum N recovery.

The farm survey (Hashemi et al., 2007) was used to calculate the average delay (in weeks) in planting the rye cover crop in each CPZ (Fig. 4). In Zone 1, it is not practical to plant the rye cover crop early enough to have an efficient N recovery. In this zone, corn is normally planted in mid- to late May due to relatively cold weather conditions (higher elevation) and is thus harvested late in September. In Zone 1, cover crops must be planted by the third week of August to collect the CAG required for maximum N recovery (Fig. 4). A rye cover crop planted with a 5- to 6-wk delay will probably only provide soil erosion prevention and will have no significant N accumulation and recovery.

Although in Zone 2 the situation is better than in Zone 1, it is still difficult to plant a rye cover crop on the recommended CPD (Fig. 4). The average delay for cover crop planting in this zone is about 5 wk, which is too much for achieving efficient N uptake. The average N uptake and relative loss in N uptake caused by the delay was calculated as 18 kg ha^{-1} and 83%, respectively, for a 5-wk delay. Farmers in northwestern regions of the state (Zones 1 and 2) may not be able to optimize the recovery of N but could benefit from combining operations, for example, seeding their cover crop while harvesting the corn.

In Zones 3 and 4, N loss can be prevented by adoption of an alternative management practice. Currently, dairy farmers in Zone 3 plant the cover crop with a 2- to 3-wk delay from the CPD, on average (Fig. 4). This delay can reduce N uptake and recovery by 49 to 66 kg N ha^{-1} (46–62%) and the economic loss related to this delay can be US\$56 to US\$75 ha^{-1} (Table 3). This N loss can be prevented by planting rye only 2 to 3 wk earlier. The use of shorter season corn hybrids can be considered as an alternative strategy that accommodates earlier harvesting and, therefore, on-time establishment of a winter rye cover crop. A 10-yr corn hybrid evaluation study in Massachusetts has shown that shorter season corn hybrids, on average, produce similar silage yield as full-season hybrids and can be harvested 7 to 14 d earlier (Herbert et al., 2009). Despite the use of shorter season corn hybrids, about a 1-wk delay in cover crop planting should be expected for Zone 3. This is because corn is rarely harvested earlier than 1 September in this or any other area in the state (Fig. 4). The CPD in Zone 3 is the first week of September and it usually takes a few days to complete the harvest, apply and incorporate manure, and then plant the cover crop.

Farmers in Zone 4 have an additional week for planting the cover crop because the CPD for Zone 4 is the second week of September. The warmer spring weather in this zone provides the opportunity to plant corn early in May and harvest it earlier in the fall. Thus, it is quite possible to plant the cover crop with no delay from the CPD. There are still some growers, however, who do not take advantage of this opportunity and who plant their cover crops later than the suggested CPD (Fig. 4).

Zone 5, closest to the Atlantic Ocean, has the warmest weather among the five zones. The CPD for this zone, which has the warmest fall weather, is the third week of September. The warmer climate for this zone also allows growers to plant corn earlier in the spring, a practice that supports early fall harvest and leaves enough time for planting the rye cover crop on time. Most of this zone is located in the urban area around Boston and the eastern part of Cape Cod, however, where only a few dairy farms are currently operating.

CONCLUSION

The time of planting of the rye cover crop is a critical factor for maximizing N recovery from fields where manure was fall applied. A delay in planting the winter cover crop can result in a dramatic reduction in N accumulation and thereby higher N leaching loss into the groundwater. A model was developed to estimate rye cover crop biomass production and N uptake and to determine CPDs for all locations in Massachusetts. In eastern areas of Massachusetts (Zone 5), the CPD is the third week of September. The warmer climate in this zone provides a longer window for planting the winter cover crop and no major change in management practices is required. Critical planting dates for the central parts of the state (Zones 3 and 4) are the first to second weeks of September. This is 1 to 2 wk earlier than what farmers are currently using. Growers in these regions should make some adjustments in their management, including selecting shorter season corn hybrids, to establish the most efficient cover crop system for maximum N recovery.

Suggested CPDs (third–fourth week of August) for northwest regions of Massachusetts (Zones 1 and 2), which are the coldest regions of the state, may not be practical for growers. This is because there is about a 4- to 7-wk overlap between the suggested cover crop planting date and the corn silage growing period.

The spatial GDD-based model, which was developed in this study for evaluating N uptake and recovery, can be used for other cover crop species and other locations. Elevation, soil data layers, and other spatial information can be added to the model to give it more robust, site-specific applications.

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