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Cover crop-based no-till for small farms: tradeoffs of termination time, method, and ecosystem services

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Cover crop-based no-till for small farms: tradeoffs of termination time, method, and ecosystem services

By

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DISSERTATION

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This thesis/dissertation was examined and approved in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Earth and Environmental Sciences by:

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On July 2, 2021

Approval signatures are on file with the University of New Hampshire Graduate School

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This wouldn’t have been possible without Nick Warren. Thank you for your steady presence, attention to detail, constant striving for better “systems,” and friendship. I am looking forward to many projects in the future. If we stay out of wrong quadrant of the research cube, I think we’ll minimize the AFLOs. Many thanks to Julia Hobbie for staying on top of things even when I was a bit scattered, and to the rest of the current Agroecology Lab—Sam Palmer, Isaac Ativor, Lilly Hartman, Shyloh Favreau, and Dave Mortensen— for being supportive and thought-provoking. I am also grateful to Seamus Wolfe, for starting this whole thing that turned into my dissertation, and to Sonja Birthisel, Jason Lilley, and Ryan Maher for creating a research community around the practice of tarping.

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ABSTRACT

Agriculture must adapt to and mitigate multiple environmental crises including climate change, overuse of herbicides, and soil degradation. Cover crops are a promising tool to do so because they protect soil from erosion, increase perenniality (i.e. year-round plant cover) and carbon contributions to farming systems, capture, recycle, and fix nitrogen, and suppress weeds through multiple mechanisms. Terminating high-residue cover crops to produce an *in situ* mulch for no-till production has added benefits of eliminating the need for tillage, protecting soil against extreme precipitation events and drought, and contributing to weed suppression. However, there are few non-chemical ways to terminate cover crops without tillage. We performed three experiments to investigate whether using reusable plastic tarps is an effective strategy to terminate a winter rye (*Secale cereale L*)- hairy vetch (*Vicia villosa* Roth) cover crop and suppress weeds for no-till production. In the first experiment, we studied the difference between clear and black plastic tarps as well as roller-crimping to terminate cover crops and found that black plastic tarps are the most efficacious method, providing significant yield benefits (+58%) to a no-till cabbage (*Brassica oleracea* var. capitata) crop compared to clear tarps and roller-crimping alone. In the second experiment, we investigated the effects of tillage and tarping in a factorial combination, with and without weed control, on cabbage yields. We found that no-till cabbage following a cover crop terminated with a black tarp produced greater or equal yields to all other treatments. In some years, the weed suppression provided by this system is significant, but weeding enhanced cabbage yields in all years. In the last experiment, we investigated the effects of termination time and termination method (tarping for 10, 20, or 30 days vs. glyphosate or roller-crimping) on ecosystem services including weed suppression and weed community dynamics, cover crop biomass C and N, mulch provisioning, residue decomposition, and N mineralization. We examine these results in two chapters. The first assesses the effects of termination time and method on weed biomass and community dynamics using a community assembly approach. We found that mulch, which is affected by both termination time and termination method, appears to be a strong driver of weed biomass and community, and that both termination time and method can select for weed species based on periodicity. Finally, we examined the tradeoffs between termination time and method on ecosystem services, planting date, and the larger picture of farming systems and environmental consequences of production systems. Differences of 10-20 days termination time significantly affected cover crop biomass, which ranged from <4 Mg ha^{-1} at the first termination time at one site to nearly 8 Mg ha^{-1} at the third termination time at another site. The effects of termination time on cover crop biomass were especially pronounced for the vetch component of the rye-vetch mixture, which doubled between the first and third termination times at both sites. Although cover crop biomass quantity and quality (C:N ratio) were drivers of ecosystem services in these systems, termination method and resulting crop planting dates also played a significant role.

INTRODUCTION

The chapters herein represent the evolution of a project centered around the practical question of how to help small farms adapt to climate change in ways premised on ecological principles. It encapsulates three experiments investigating high-biomass cover crops for no-till production without herbicides. Rather than providing a justification for the project and summary of the themes, which you will read repeatedly in each chapter, here I have included a narrative of how this dissertation came to be along with the things that are not said in the chapters themselves.

The first experiment came to fruition because of a motivated undergraduate, Seamus Wolfe, who contacted me about organic no-till vegetable production. Our being at UNH was a complete coincidence, since he reached out to me through my blog. With Rich Smith and Nick Warren, we designed an experiment that built on the failures and successes of previous cover crop-based no-till research. There was clearly a need for alternative ways to terminate cover crops effectively and suppress weeds; mechanical termination with a roller-crimper was not viable in our northern climate with a short growing season. Tarps were gaining popularity among small farmers, popularized by books like *The Market Gardener* (Fortier and Bilodeau, 2014), but were (and still are) typically used on bare soil or minimal crop residue. We thought tarps might be a way to meet farmers "where they are" in terms of the tools they were using while advancing the use of high-biomass cover crops and no-till. We grew a rye-vetch cover crop and then deployed clear and black tarps for different durations before growing a no-till transplanted cabbage crop.

I never intended to conduct my dissertation research on this topic, but the results were interesting and promising enough that I thought it was worth applying for a grant from Northeast SARE, which we received. The next experiment, initiated before we knew if we had received funding, built on the first experiment. For this experiment, we included tillage as a factor. Knowing that adequate weed suppression is critical to the success of cover crop-based no-till, we also included weeding as a factor. This experiment, which we ran over two years on my mother's land in Maine, wouldn't have been possible without substantial help in the field from my mom. We had to harvest the cabbages slightly early that year when porcupines discovered our field and started helping themselves to nearly fully formed heads of cabbage.

The next year, my mom and I constructed a chicken wire fence around the entire field that we secured to the ground with sod staples and fortified with an electrified line on top, hoping that it would gently—but not too gently—keep the climbing porcupines out. After our data (i.e. cabbage and weeds) had been collected, the fence was breached and entire cabbages started going missing. It was different than porcupine damage; whole plants were completely removed. When we followed what appeared to be a trail, we found cabbages floating in the river, apparently taken by beavers stocking up for winter. Taking the fence down was even more tedious than putting it up. Over the course of these two years, we also shared with people, donating over 4,000 pounds of cabbage to the local foodbank. As someone who doesn't thrive on customer interactions, it was a great feeling to feed people but not have to sell food.

In the third experiment, we grew no food. This experiment built on the need to refine the cover crop-tarp-no-till "system" since we were moving beyond "proof-of-concept" experiments. It was a feat of time management, with a flurry of field activity to look at the dynamics of tarp application time and tarp duration, all while conducting the second year of the second cabbage experiment concurrently in an adjacent field. The experiment went smoothly and I was relieved not to have to worry about porcupines. However, at our final weed harvest I noticed that some weed species were clearly showing signs of herbivory. Wildlife is wonderful, and also an issue in these diverse landscapes. Farmers here a lot to manage. We conducted the second year of the experiment at Woodman Farm at UNH, beginning the major portion of field work when I was 8.5 months pregnant. I did what I could until I couldn't use a pair of scissors anymore and was not very helpful. After two trips to UNH from Maine with my newborn daughter, mom, and husband on parental leave from his job, I realized that doing fieldwork that summer was unreasonable. Nick Warren and the rest of the Agroecology Lab that summer did an incredible job managing the time-sensitive field and lab work and the single set of missing data is entirely my fault. This was, I believe, the year the Agroecology Lab fell in love with OneNote, which made coordination much easier.

On good days, I feel like this research is helpful to farmers and is an improvement in sustainability over current production systems. Maybe some clever materials scientists will come up with alternatives to plastic that are truly biodegradable. After all, this system is really about a light-occluding material to manage plants—not just plastic. On bad days, I picture landfills and incinerators piled high with plastic, not to mention the microplastics and chemical additives seeping into our soils and waterways. I am not convinced plastic, as we currently produce and manage it, is better than glyphosate, and I don't want to promote a practice that in the end does more harm than good.

That highlights the theme of this dissertation: tradeoffs. This applies to agricultural systems themselves and research to improve agricultural systems. There are tradeoffs within each farming system, which is captured by the question discussed in Chapters 2 & 4 of the best use of limited growing degree days—for cover crop growth, tarping, or cash crop production? There are tradeoffs between farming systems, which is captured by the discussion in Chapter 4 of the pros and cons of glyphosate vs. tarps to terminate cover crops. And finally, there are tradeoffs between different research approaches to the question of increasing sustainability in agriculture. Do we target research questions toward the largest acreage, or the largest number of farms? The number of small farms is increasing while the number of larger farms declines, and these small farms are often neglected in research. Do we seek to make transformational changes to our agricultural systems (e.g.. breeding perennial grains), or do we attempt small but significant changes to current production systems? Of course we must do all of the above.

In this dissertation, I have asked very applied questions that are mostly relevant to small-scale producers. The experimental systems here represent small but significant changes to current production systems. The first chapter is a “proof-of-concept” about the cover crop-tarp-no-till system from our first experiment and has already been published as a preliminary report. The second chapter, from our second experiment, is another iteration of the “proof-of-concept,” with refinements. The third chapter, from our third experiment investigating tarp application time and duration, delves into the ways these factors, in conjunction with cover crop performance, affect weed community assembly. The fourth chapter is a discussion of optimizing the cover crop-tarp-no-till system and highlights the tradeoffs of planting date and multiple ecosystem services.

When we applied for the SARE grant, we decided to submit to the “Research for Novel Approaches” program. This was meant to fund “proof-of-concept” projects that have strong potential but need further refinement before recommending farmer adoption. As a testament to the success of the project, I would say this is no longer a proof-of-concept, but a fully fledged system that is being adopted and even promoted by farmers. I received this email from a farmer in Vermont:

> A couple years ago I saw you present on rolling and tarping rye-vetch cover crops for no-till production. We tried our first section this year and were really impressed with the results, it was a great broccoli crop and incredible weed suppression. We're planning on scaling up this growing method for next year and have some great stands of rye and vetch growing now!

Perhaps it is a sign of progress when I look back and say “why did we do that?” For example, why did we apply tarps so early in the second experiment, before the vetch had really grown to its full potential? The answer is that we hadn’t yet learned the lessons from the third experiment—that letting cover crops grow may a more valuable use of growing degree days than tarping for an extended period. Other times I ask “why didn’t we do that?” For example, why didn’t we quantify population density of the cover crops in our experiments? Why didn’t I use thermal units as a point of reference for cover crop performance in our first paper (Chapter 1)? The importance of refining the units we use so they can best help us interpret the results is another theme that has emerged from my dissertation research that will guide me going forward.

Although I am admittedly sick of tarping and ready to move on to some other questions in the near future, this research has enhanced my love of cover crops and belief that there is tremendous potential for cover cropping to be a transformational change in our agricultural systems across all scales of farming. We are only just beginning to refine cover crop management and understand the extent to which cover crops can restore degraded soils, help adapt to and mitigate climate change, and alter our current paradigm of weed management.

I. CHAPTER 1: INVESTIGATING TARPS TO FACILITATE NO-TILL ORGANIC CABBAGE WITH HIGH RESIDUE COVER CROPS[1]

Abstract

High-residue cover crops can facilitate organic no-till vegetable production when cover crop biomass production is sufficient to suppress weeds (>8000 kg ha^{-1}), and cash crop growth is not limited by soil temperature, nutrient availability, or cover crop regrowth. In cool climates, however, both cover crop biomass production and soil temperature can be limiting organic no-till. In addition, successful termination of cover crops can be a challenge, particularly when cover crops are grown as mixtures. We tested whether reusable plastic tarps, an increasingly popular tool for small-scale vegetable farmers, could be used to augment organic no-till cover crop termination and weed suppression. We no-till transplanted cabbage into a winter rye (*Secale cereale* L.)-hairy vetch (*Vicia villosa* Roth) cover crop mulch that was terminated with either a roller-crimper alone or a roller-crimper plus black or clear tarps. Tarps were applied for durations of two, four, and five weeks. Across tarp durations, black tarps increased the mean cabbage head weight by 58% compared to the no tarp treatment. This was likely due to a combination of improved weed suppression and nutrient availability. Although soil nutrients and biological activity were not directly measured, remaining cover crop mulch in the black tarp

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[1] This chapter has been published as:

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treatments was reduced by more than 1100 kg ha^{-1} when tarps were removed compared to clear and no tarp treatments. We interpret this as an indirect measurement of biological activity perhaps accelerated by lower daily soil temperature fluctuations and more constant volumetric water content under black tarps. The edges of both tarp types were held down, rather than buried, but moisture losses from the clear tarps was greater and this may have affected the efficacy of clear tarps. Plastic tarps effectively killed the vetch cover crop whereas it readily regrew in the crimped but uncovered plots. However, emergence of large and smooth crabgrass (*Digitaria* spp.) appeared to be enhanced in the clear tarp treatment. Although this experiment was limited to a single site-year in New Hampshire, it shows that use of black tarps can overcome some of the obstacles to implementing cover crop-based no-till vegetable productions in northern climates.

Introduction

Soils on vegetable farms are often compacted and have poor aggregation as a result of intensive tillage and traffic (Wolfe et al., 1995; Haynes and Tregurtha, 1999). Reducing tillage and planting cover crops are two strategies for improving soil aggregation, infiltration, and organic matter retention. No-till seeding cash crops into terminated high-residue cover crops like winter rye (*Secale cereale*) and hairy vetch (*Vicia villosa)* has been researched extensively in both herbicide-based no-till and organic rotational no-till grain production systems (Clark et al., 1994, 1997; Mischler et al., 2010; Smith et al., 2011; Ryan et al., 2011; Mirsky et al., 2012; Reberg-Horton et al., 2012). Although similar high-residue cover crop systems for vegetable production were introduced in the 1990s (Morse, 1999), implementing them has remained challenging, especially in organic vegetable systems, because of highly variable results.

While some researchers have reported vegetable yields in organic cover crop-based no-till comparable to conventional tillage (Ciaccia et al., 2016; Jokela and Nair, 2016a, 2016b), others have reported reduced yields and/or profits (Leavitt et al., 2011; Delate et al., 2012; Luna et al., 2012). In order to reduce risk and make these systems viable for farmers, we must address the production constraints that have led to the observed variability in vegetable crop response. Furthermore, we must begin to address the lack of scale-appropriate equipment that limits adoption of reduced tillage practices by many vegetable growers (Lowry and Brainard, 2017). Tarps may serve as a means to gain greater management control over high-residue cover crops, without the need for specialized or expensive equipment.

High-residue cover crop-based no-till

Implementing no-till with the use of high residue cover crops can change the soil environment in multiple ways, with both positive and negative effects on cash crop growth. The presence of a high residue mulch minimizes evaporative losses and generally leads to higher soil moisture content, which is a benefit during dry periods (Teasdale and Mohler, 1993). Even as little as 2 Mg ha^{-1} of surface residue can increase soil porosity, aggregation, and moisture content (Mulumba and Lal, 2008).

Mulch also lowers the maximum soil temperature, which can limit plant growth and nutrient mineralization. Lower soil temperatures in high-residue systems have been associated with reduced vegetable yields in northern climates. For example, zucchini, tomato, and bell pepper yields were reduced 41–89% in Minnesota when grown under a rye-vetch mulch (Leavitt et al., 2011). In Iowa, bell pepper yields in cover crop-based no-till were comparable in one season, but lower in another and the authors suggested that the difference between years was a result of temperature and nutrient availability in no-till (Jokela and Nair, 2016b). Cabbage is less temperature-sensitive than these other summer crops, but delayed cabbage growth as a result of cool soils under cover crop residue has been observed in cool spring and fall conditions in the southeastern United States (Hoyt, 1999). In New York, soil temperatures under rye mulch were 2-3°C lower than bare soil, and cabbage yields were reduced 21%, although the authors speculated that temperature was not the limiting factor in cabbage yields (Mochizuki et al., 2008).

Previous research has demonstrated that 8-9 Mg ha^{-1} of cover crop biomass is needed prior to termination to obtain satisfactory weed suppression without additional weed control (Smith et al., 2011; Mirsky et al., 2012). These biomass levels are hard to achieve without early seeding of the cover crops, especially in northern climates (Lawson et al., 2013). Hairy vetch, a popular legume cover crop to mix with rye, can itself become a weed if not effectively terminated (Boydston and Williams, 2017). However, asynchronous maturation of rye and vetch can present problems for mechanical termination, which is only effective for vetch after early podset (Mischler et al., 2010; Boydston and Williams, 2017).

Tarps for weed suppression

Reusable tarps are an emerging weed management technique for small-scale farmers that has been popularized by farming books such as *The Market Gardener* (Fortier and Bilodeau, 2014). In the scientific literature, use of both clear and black tarps is often referred to as "solarization," but the use of black tarps is often distinguished as "occultation" within the farming literature. Most solarization research has employed clear tarps on bare soil and while weed control has been a focus of some studies, the primary goal has been pathogen control (Horowitz et al., 1983; Standifer et al., 1984; Stapleton and DeVay, 1986; Stapleton, 2000; El-Keblawy and Al-Hamadi, 2009). The efficacy of solarization as a weed management technique using clear tarps is dependent on the temperatures achieved, moisture, and the weed species present. Increased temperatures can lead to direct thermal killing, a breakage in dormancy resulting in fatal germination, or the demise of weakened seeds through biological attack (Rubin and Benjamin, 1984). Most studies have occurred in hot climates such as Israel and parts of California and when used on bare soil in these climates, both clear and black plastic suppress most weeds as soil temperatures exceed 40–45°C (Horowitz et al., 1983; Standifer et al., 1984). In cooler, less sunny climates, clear plastic can stimulate rather than kill weeds (Bond and Burch, 1989). To the best of our knowledge, there are no reports in the scientific literature of using tarps on cover crops directly.

Tarps could be an effective tool for addressing some of the current limitations to organic no-till. Tarps eliminate the need for specialized mechanical termination equipment; simple, inexpensive lawn rollers or disengaged rototillers work to lay the cover crop down prior to tarp application. Tarps also provide flexibility in timing because they eliminate the requirement to terminate cover crops at a specific growth stage. Weed suppression via tarps could allow for no-till crop production even in the absence of high quantities of cover crop biomass (e.g., < 8 Mg ha^{-1}), thus allowing a broader range of cover crop species and productivity. Furthermore, if tarps increase nutrient mineralization as has been suggested (Stapleton, 2000), they could help overcome some of the problems associated with cold soils and reduced nutrient availability observed in previous cover crop-based no-till studies.

Objectives

The objectives of this experiment were to investigate the effects of tarp type and time of crimping and tarp application on cabbage yields and weed growth within a cover crop-based no-till production system in a northern climate (New Hampshire). This experiment was conducted in a single site-year and will not be repeated; however, the results have been used to inform the design of further experiments.

Methods and Materials

Experiment Site

The experiment was conducted at the University of New Hampshire's Woodman Horticultural Farm (43° 08' 59" N, 70°56'28"W). The soil is classified as Charlton fine sandy loam (Coarse-loamy, mixed, superactive, mesic Typic Dystrudept). A single composite soil sample (0–20 cm) was taken on March 1, 2016 and analyzed at the Pennsylvania State University Soil Lab. Nutrients were extracted using Mehlich III. Soil pH was 5.9 and all nutrients were at or above optimum levels except K, which had a low soil test value (150 mg kg^{-1}). The experimental field had a history of mixed vegetable and cover crop production and had been managed organically for a least the previous three years.

Experimental Design and Treatment Structure

Treatment structure was factorial with three crimp/tarp application dates [June 2 ("early", 5 weeks prior to planting cabbage), June 9 ("mid", 4 weeks prior to planting), and June 22 ("late", 2 weeks prior to planting)], and three tarp treatments (black, clear, and no tarp). Treatments were imposed as a split-plot randomized complete block design with four blocks. The main plot factor was cover crop crimp/tarp application, hereafter referred to as "crimp date". Main plots were 3 x 18 m. The sub-plot factor was tarp type and sub-plots were 3 x 6m.

Field Activities

After the field was disked, rye (*Secale cereale,* VNS*)* and hairy vetch (*Vicia villosa,* VNS) were broadcast at a rate of 45 kg rye ha^{-1} and 13 kg vetch ha^{-1} on September 21, 2015.

Crimping was performed with a 3 m rear-mounted roller crimper (I & J Manufacturing, Gordonville, PA). Rye had reached >50% anthesis by the early crimp date and vetch had reached early flower, late flower, and early podset on the early, mid, and late crimp dates, respectively. Tarps, which were applied immediately after crimping, were new, 4 mil (0.10 mm) low density polyethylene film (Visqueen) and were held in place by a combination of staples and sand bags on the edge of the tarps, placed at approximately 1 m intervals.

We removed the tarps on July 7, 2016 and transplanted cabbage (*Brassica oleracea* var. capitate 'Farao'; Johnny's Selected Sees, Winslow, ME) by block on July 7, 8, and 10 into holes established manually with a pinch point bar. Prior to transplanting, cabbage seedlings were grown in potting media approved for organic production in 72-cell trays in a greenhouse for six weeks. We planted three rows of cabbage per plot, with 61 cm between rows and 41 cm between plants. Each plant received 70 g Pro-Gro fertilizer (3.0-1.7-4.2, N-P-K) in a separate hole at the time of transplanting. This rate is equal to 120 kg ha^{-1} N at a plant density of 34,600 ha^{-1}.
We irrigated once after tarp removal and prior to transplanting on July 7, and once per week the following two weeks. Each irrigation delivered approximately 2 cm of water using a rain gun (Rainbird, Azusa, CA). No weeding was performed.

Field measurements

We measured cover crop biomass immediately prior to crimping and tarp application in each sub-plot for early, mid, and late crimp dates by clipping plants with stems originating within one 0.25 m^2 quadrat. Rye and vetch were dried in an oven at 65° C until they reached a constant weight. After removing tarps on July 7 but prior to transplanting cabbage, we measured the mass of the dead cover crop mulch in each treatment by cutting around the interior edges of a 0.25 m^2 quadrat in each subplot and drying to a constant weight. On September 14, we harvested cabbage, weeds, cover crop regrowth, and dead cover crop mulch. Ten cabbages from the center row of each plot were harvested. Some cabbages had visible damage from animal herbivory and were not included; a minimum of seven cabbage heads was used to calculate mean head weight. Weeds and cover crop regrowth were clipped at the soil surface, separated to species, and dried to a constant weight. Mulch was measured using the above method.

To understand environmental conditions that moderate the effects of tarps, soil volumetric water content and temperature were measured and logged hourly using GS3 capacitance sensors inserted horizontally at depth of 3 cm and EC2O dataloggers (Decagon Devices, Pullman, WA). Measurements were taken in three blocks in the three treatments of the "early" main plots as well as a 0.25 m^2 bare plot where the cover crop was removed after crimping.

Statistical analyses

We used linear mixed models to calculate treatment effects on cabbage weight, cover crop/mulch biomass, and total weed biomass, all of which met the assumptions for analysis of variance (ANOVA). Crimp date, tarp treatment, and their interaction were treated as fixed effects with block as a random effect. For these analyses, we used R package lme4 (Bates et al., 2015). Pairwise comparisons were made using Tukey's HSD with alpha=0.05.

To investigate treatment effects on individual weed species, which did not meet ANOVA assumptions, we performed an indicator species analysis (Dufrene and Legendre, 1997) using PC-ORD (Version 6) (McCune and Medford, 2011). Indicator species analysis is unable to accommodate a factorial treatment structure and therefore only tarp treatment was considered. This decision was made on the basis of a non-metric multidimensional scaling ordination and permutational multivariate analysis of variance performed using the R vegan package 2.3-5

(Oksanen et al., 2016) that indicated tarp treatment, not crimp date, most strongly influenced weed communities. Only *Digitaria* spp. and vetch regrowth had indicator values with p-values <0.05; therefore, for subsequent analyses and graphing we kept these species separate. All other weed species were included in the category “other”.

Results and Discussion

Cover crop

Cover crop biomass was 6.2 Mg ha^{-1} and did not increase with later crimp date (p=0.70). While some researchers have found that delaying rye termination increases biomass (Mirsky et al., 2011), others have not (Wayman et al., 2015). These results suggests that cover crop biomass had already peaked at the earliest crimp date in our study.

Yield

Average cabbage head weight was highest in the black tarp treatment and there was no difference between clear and no tarp treatments. This main effect was significant across all three crimp dates and cabbage following the black tarp treatment weighed 58% more than that following the no tarp treatment (Fig. 1.1). It is possible that differences in cabbage weight would not have been so great if cabbages in the no tarp treatment had been transplanted immediately after crimping instead of waiting to transplant all cabbages at the same time (after tarp removal), but we chose to standardize the crimping and transplanting days. Despite the main effect of tarp treatment on cabbage weight, a notable trend was apparent within the black tarp treatment of declining head weight with later time. This tarp treatment by crimp date interaction did not reach significance, but the marginal p value (p=0.10) warrants mention and the simple means have been included in Fig. 1.1. Precipitation was below average for August and September (Fig. 1.2), which likely contributed to low head weights.

There are several potential mechanisms for the observed differences in yield (cabbage weight) across the tarp treatments, and while we did not directly test these mechanisms, the data suggest that a combination of weed dynamics and biological activity/nutrient mineralization may be responsible for the differences.

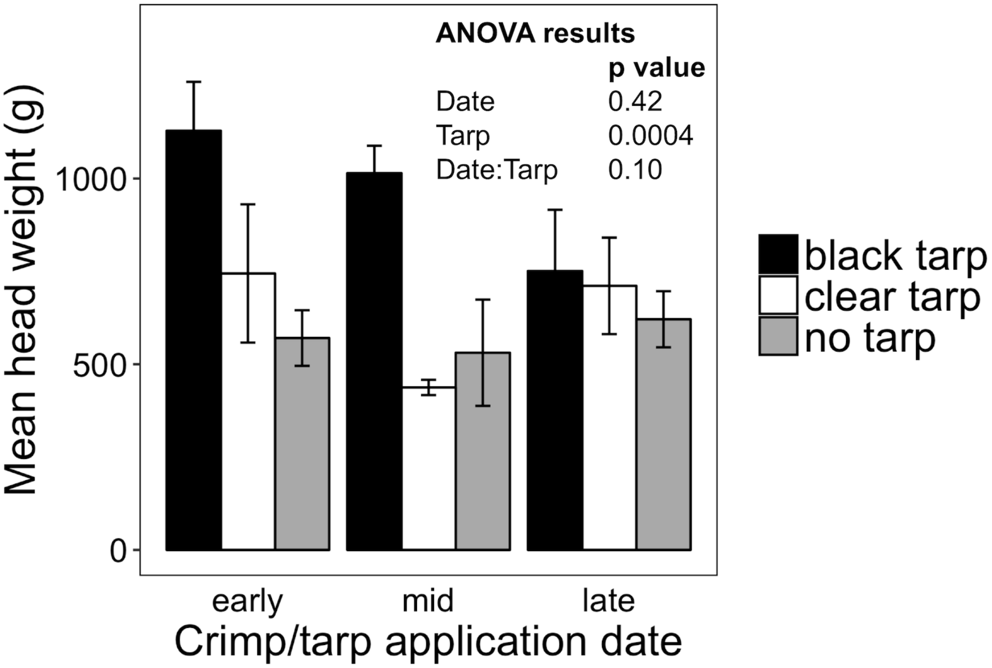

Figure 1.1: Mean weight of cabbage heads that were no-till transplanted into a rye-vetch cover crop terminated with a roller crimper. Tarp treatments (black, clear, or no tarp) were applied immediately after crimping for a duration of five (“early”), four (“mid”), and two (“late”) weeks prior to planting cabbage. There was a main effect of tarp type on cabbage weight (black>clear=none), but simple means are shown because of a trend of decreasing cabbage weight within the black tarp treatments. Data are means ± standard error (n=4).

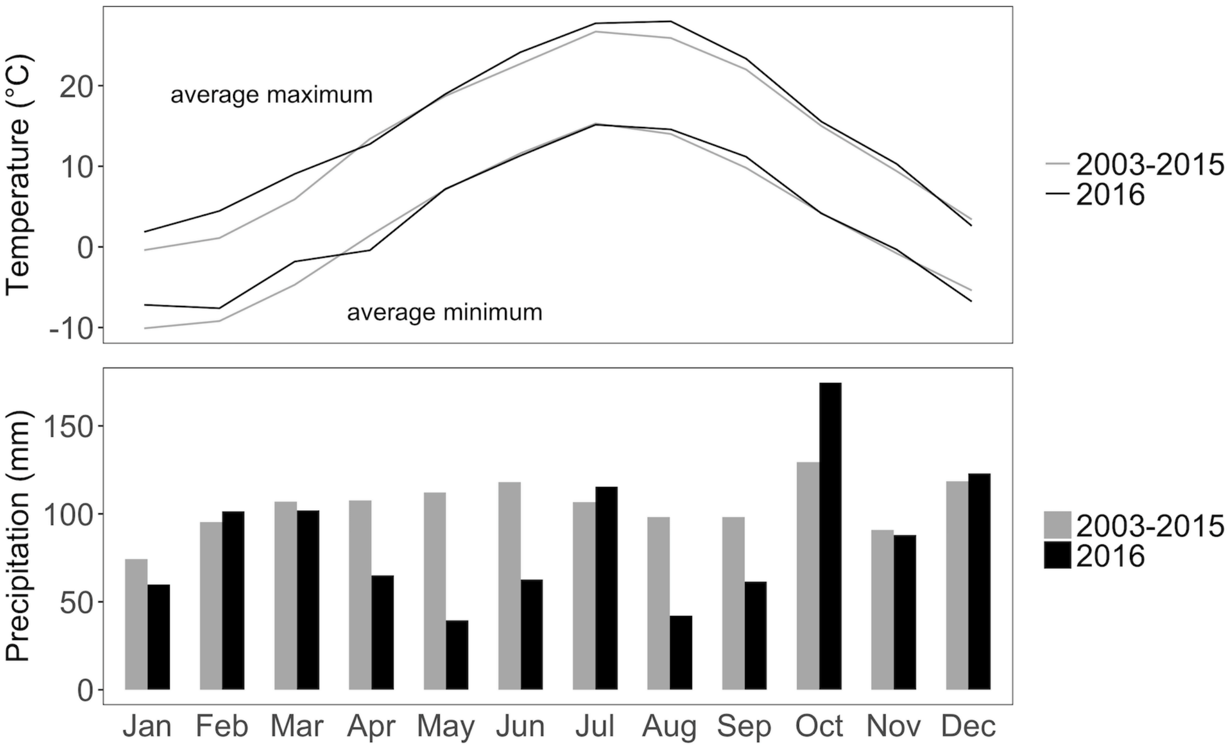

Figure 1.2: Average monthly minimum and maximum temperatures and precipitation in 2016 vs. historical data (2003-2015) at the nearby UNH Kingman Research Farm weather station in Madbury, NH (43.17° N 70.93°W).

Weeds

Weed biomass alone cannot explain differences in yield, as there was no correlation between weed biomass at cabbage harvest and cabbage weight (R^2=0.015). There were, however, differences in the weed communities in the different treatments. Vetch was strongly associated with the no tarp treatment (indicator value= 96, p=0.0002). Living vetch was visible in the no tarp treatments after crimping, and the data clearly show that crimping alone did not kill vetch, even when crimping was delayed until late June (late) when early podset had begun (Fig.1.3).

No living plants were visible in either the clear or black tarp treatments when the tarps were removed. The weed community that emerged after the clear tarps were removed was dominated by large and smooth crabgrass (*Digitaria sanguinalis* and *Digitaria ischaemum).* *Digitaria* spp. were pooled when weeds were sorted and together they had an indicator value of

62 (p=0.02) for the clear tarp treatment. This is strong evidence that the clear tarps stimulated crabgrass emergence. Large crabgrass emerges over a long period, with 10% emergence at 280 soil degree days (base 9°C) and 95% emergence at 1500 degree days under irrigated conditions (Myers et al., 2004). It is possible that the higher temperatures under the clear tarp encouraged greater emergence over a shorter period of time once the tarps were removed. While there was no correlation overall between final weed biomass and cabbage weights, the treatment with the highest weed biomass (mid-clear) was >80% crabgrass and also had the lowest cabbage weights (Fig. 1.3).

Because of a significant tarp by crimp date interaction on weed biomass (p=0.007), we are unable to draw broad conclusions about the effects of tarp treatment or crimp date on weed biomass. When simple means were analyzed within each crimp date, the only differences in weed biomass between tarp treatments were seen for the "mid" tarp date, where weed biomass in the clear tarp treatment was significantly higher than the others (p=0.002). However, the final weed biomass does not capture the timing of weed emergence and growth, which influences the level of competition with the crop. Significant crabgrass growth was observed in the clear treatments as early as three weeks after transplanting possibly during the critical period for crop-weed competition (Weaver, 1984), whereas weeds were not apparent in the black tarp treatments until later.

Tarps used for solarization are generally applied after irrigation or rain so that both soil moisture and temperature requirements can be met to induce fatal weed germination and direct thermal killing of weed seeds (Rubin and Benjamin, 1984). We did not irrigate prior to tarp application in this experiment. However, there was a rain event of 3.9 cm on June 5, four days before the "mid" crimping and tarp application date that increased soil moisture (visible in Fig.

1.4). The higher initial soil water content did not lead to greater weed reduction under tarps; instead, this tarp date had the highest weed biomass under clear tarps of the three dates.

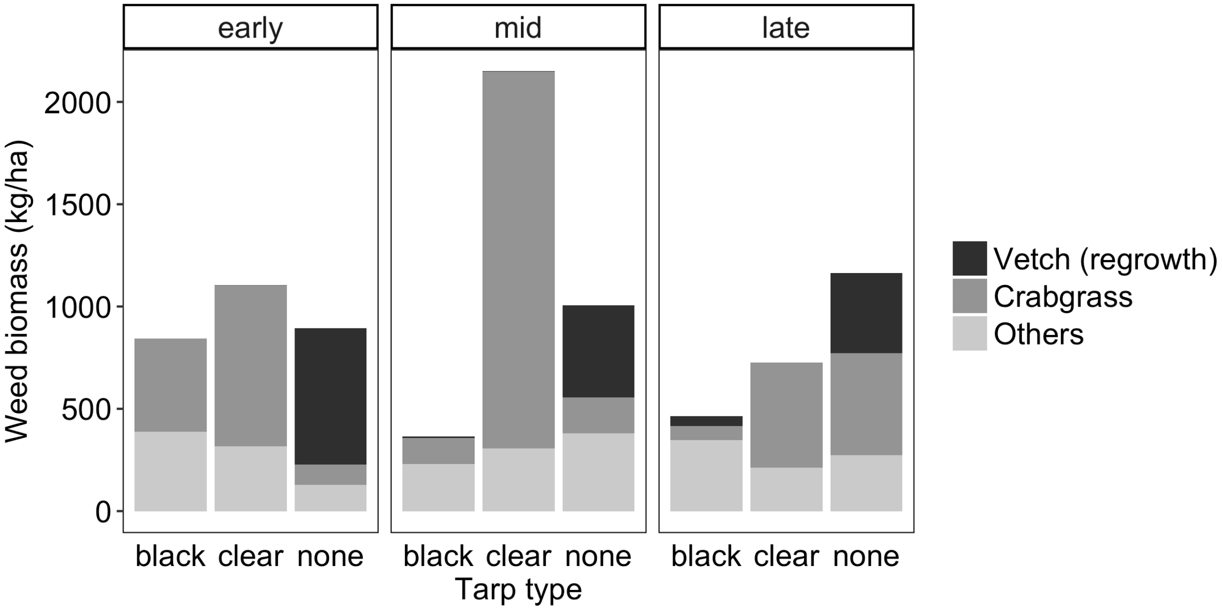

Figure 1.3: Weed biomass by species at the time of cabbage harvest in treatments in which black, clear, or no tarps were applied to crimped cover crops. Early, mid, and late are the timing of crimping/tarp application and correspond to durations of five, four, and two weeks, respectively, prior to planting cabbage. Data are means (n=4).

Mulch, Soil Temperature and Moisture

Another factor that could have influenced cabbage growth is nutrient availability. We did not directly quantify nutrient availability, but we measured the amount of cover crop mulch remaining on the soil surface by the time of harvest, which we interpret as an indirect measurement of biological activity.

Although there were no differences in cover crop biomass between the plots prior to treatment application, there were differences in the amount of dead cover crop mulch remaining at tarp removal and cabbage harvest. At time of tarp removal, there was a main effect of tarp treatment, but not crimp date, on remaining mulch. Clear and no tarp treatments had >1100 kg ha^{-1} more mulch than where black tarps had been (p=0.01) (Fig. 1.5). When mulch was measured again at cabbage harvest, the differences remained significant (p=0.0004). Although the total amount of mulch decreased between the time of tarp removal in July and cabbage harvest in September, the magnitude of the difference between treatments appeared similar between these times, suggesting that the increased rate of decomposition of the mulch in the black tarp treatment occurred primarily during the tarping period, not after the tarps were removed.

Temperature, moisture, and residue quality all influence surface residue decomposition rates, and black tarps appear to facilitate environmental conditions that encourage microbial activity. While laboratory experiments have elucidated relationships between either temperature, moisture, or residue quality with decomposition rates (e.g. Quemada and Cabrera, 1997), the complex interactions among factors in field settings make modeling surface decomposition difficult (Findeling et al., 2007). While the patterns of soil temperature and moisture in the different treatments are obvious, how this led to greater mulch decomposition in the black tarp treatment is not.

Temperature alone is unlikely to have caused the accelerated mulch decomposition under black tarps, as daily maximum soil temperatures were lowest there in the early treatment for which we have data (Fig. 1.4). This highlights a key difference between using black tarps on bare soil where there is direct tarp-soil contact, and on a cover crop, which creates an air gap between the soil surface and the tarp. It is possible, however, that the smaller daily temperature fluctuation under black tarps contributed to more stable conditions for biological activity despite the lower mean temperatures. The effect of fluctuating vs. constant temperature is unclear, but there is evidence that temperature fluctuations can decrease biological activity in soil

(Biederbeck and Campbell, 1973; Lomander et al., 1998). Neither clear nor black tarps achieved temperatures comparable to other solarization studies (>40° C) investigating weed suppression. Based on the temperatures under the black tarps in this study (Fig. 1.4), it is unlikely that direct thermal killing of weed seeds occurred.

It is possible that soil moisture had more of an effect on mulch decomposition and biological activity than temperature. All treatments began with relatively low water content, but soil moisture was maintained under the black tarps and declined steeply under the clear tarps (Fig. 1.4). There was visible condensation on the underside of the clear tarps, and the data show that this water was lost from the soil over time. The issue of moisture loss from the clear tarp treatments may have been alleviated if the edges had been buried. Moisture where there was no tarp was more variable and responded to rain events (Fig. 1.4). Under normal field conditions, surface residue decomposition occurs in pulses, not at a steady rate, in response to changing soil moisture (Findeling et al., 2007). Constant soil moisture conditions in conjunction with steadier temperatures under the black tarp may have facilitated more consistent and thus greater overall mulch decomposition. Because mulch provides weed suppression and moisture retention throughout the growing season, there is a tradeoff between increased residue decomposition that releases nutrients and decreased mulch. Additional research will be necessary to better understand how black tarps alter the biological and edaphic properties of the soil in these types of systems.

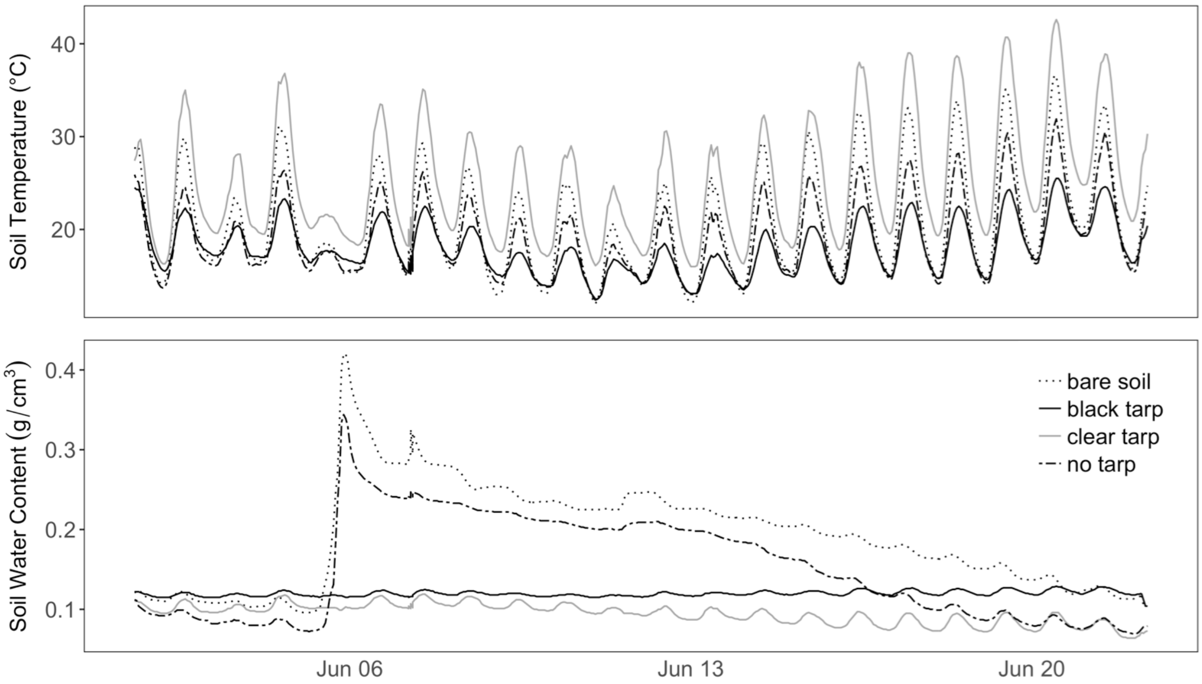

Figure 1.4: Average soil temperature and volumetric water content at 3 cm depth in the "early" treatment in which crimping and tarp application occurred on June 2. Black, clear, and no tarp treatments all had cover crop residue on the soil surface, but the residue was removed where the "bare soil" sensor was placed. Data are means (n=3).

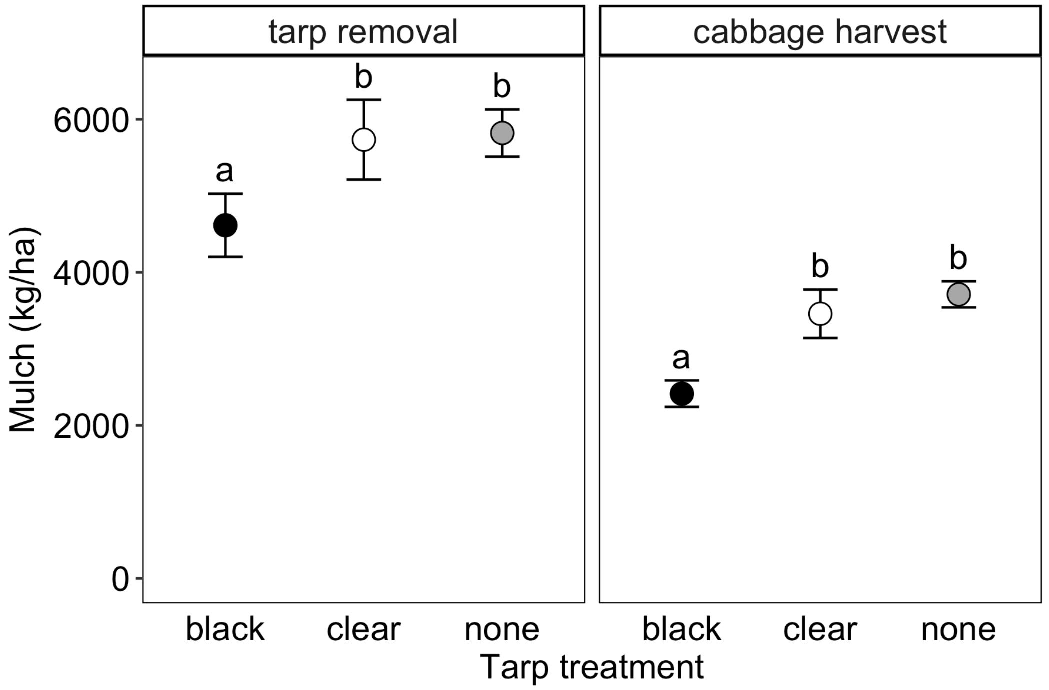

Figure 1.5: Dead cover crop mulch remaining on the surface at tarp removal (July 7) and time of cabbage harvest (September 14). Black, clear, or no tarp were applied to cover crops immediately after rolling with a roller-crimper. Means did not differ by crimp/tarp application date. Letters denote significance at $p<0.05$ using Tukey's test within each sampling time point. Data are means ± standard error (n=12).

Conclusions

This experiment showed tarps have promise in overcoming some of the constraints of current cover crop-based no-till systems for organic vegetable production in cold climates. Our data indicate that both black and clear tarps effectively terminate cover crops, but clear tarps increased crabgrass emergence after tarp removal. Different conditions (i.e. more rain or irrigation prior to tarp application), and burial of the tarp edges may produce different results than the ones we observed in this limited study. When averaged across all crimp dates, black tarps increased cabbage weight by 58% compared to rolling/crimping alone. The mechanisms for this are not completely clear, but likely involve a combination weed suppression and nutrient mineralization. We did not measure soil nutrients directly, but observed more rapid decomposition of cover crop mulch in the black tarp treatment, indicating greater biological activity and release of nutrients. Importantly, tarps are accessible to small-scale producers and may even offer advantages over other methods of mechanically killing cover crops. While we used a roller-crimper in all treatments, it is possible that alternative implements such as disengaged rototillers or lawn rollers, which temporarily lay down tall cover crops, could be used to prepare for tarping thus reducing the need for specialized equipment. Vetch is of particular importance to growers in cooler climates because it is a winter hardy legume, and was successfully terminated using tarps. Tarps appear to facilitate small-scale, no-till vegetable production by increasing flexibility for when cover crops can be terminated. Further research is necessary to understand the relationships between air temperature, tarp duration, weed dynamics, and nutrient mineralization. This would allow farmers to optimize tarp duration depending on the weather and their individual production goals.

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II. CHAPTER 2: TILLAGE AND TARPING EFFECTS ON ORGANIC CABBAGE YIELDS AND WEEDS FOLLOWING A RYE-VETCH COVER CROP

Abstract

Small-scale vegetable farmers are interested in cover crops and reduced tillage, but scale-appropriate technology and equipment are necessary to expand these practices to the growing segment of small farms. We sought to determine the efficacy of tarps, an increasingly popular tool on small farms, to terminate overwintering cover crops and provide weed suppression for subsequent no-till cabbage production. In three fields over two seasons in Maine, we grew a winter rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* L.) cover crop which we managed by a factorial combination of tillage (No-till, Till) and tarping (Tarp, No-tarp) in June, followed by a transplanted cabbage crop (*Brassica oleracea* var. capitata) in July. Cover crop biomass ranged from 2.8–4.5 Mg ha^{-1}. Mean cabbage head weights in No-till/Tarp were greater than (Year 1) or equal to (Year 2) Till/No-tarp and Till/Tarp in weeded and unweeded subplots. In Year 1, mean cabbage head weight in weeded subplots was 48% greater in No-till/Tarp than Till/No-tarp. In unweeded subplots, this difference was 270%, highlighting the efficacy of the No-till/Tarp system at reducing the effect of weeds in comparison to Till/No-tarp. In Year 2, weeding had a stronger effect on mean cabbage weight across all treatments, with unweeded plots failing to produce marketable heads (i.e. >300g). With the exception of No-Till/No-tarp, mean cabbage weight across all weeded subplots was equal. Tarping had a strong effect on weed biomass and weed community composition measured at the time of cabbage harvest in unweeded subplots. Tarps effectively facilitated cover crop mulch based no-till and we propose that this system has potential as an adaptive strategy for farmers in the face of projected climate change.

However, both cover crop production and tarping shorten the growing season, and we discuss tradeoffs using the metric of growing degree days to quantify opportunity costs.

Introduction

Reusable plastic tarps are increasingly common for small-scale organic farmers to manage weeds and facilitate reduced tillage vegetable production. The use of tarps has been popularized by farming and market gardening books (Fortier and Bilodeau, 2014; Mefferd, 2019; Mays, 2020), but has received little attention from researchers (Birthisel and Gallandt, 2019; Lounsbury et al., 2020; Rylander et al., 2020a, 2020b). Many of the farmers featured in these publications apply large amounts of compost (e.g., resulting in mulch depths of 3–10 cm) to bury weed seeds, then deploy tarps between cash crops to manage weeds and crop residue. This strategy can be effective, but is limited by the amount of high-quality compost available and has the potential to contribute to nutrient pollution—especially when manure-based compost is used (Small et al., 2019). In states where nutrient management plans are mandatory and phosphorus applications are restricted, this farming system may face regulatory constraints (Coale et al., 2002; Kogelmann et al., 2004). Alternatives to large amounts of compost are necessary to facilitate more widespread adoption of reduced tillage practices on small-scale farms.

In situ mulch from cover crops is an alternative to compost for weed suppression. Previous efforts to develop reduced tillage systems based on cover crop mulch have had variable results and limited adoption (Brainard et al., 2013; Halde et al., 2017). Incomplete cover crop termination, inadequate weed control from low cover crop biomass, and reduced vegetable yields have hampered progress in these systems (Mochizuki et al., 2007; Leavitt et al., 2011). These issues are especially challenging in northern latitudes, where cover crop biomass production is typically lower and growing seasons are short (Halde et al., 2017). Furthermore, small-scale farmers face equipment constraints and do not typically have the tools required for managing high biomass cover crops (O'Connell et al., 2014; Lowry and Brainard, 2017; Kornecki and Reyes, 2020).

Integrating tarps with cover crops may overcome some of the barriers that previously limited adoption of cover crop mulch based systems (Lounsbury et al., 2020). This would improve the sustainability of tarping practices that farmers are already using (i.e. with compost or bare soil). In addition to weed suppression, cover crops provide myriad benefits including erosion prevention, organic matter contributions, year-round living roots, nutrient capture, and N fixation (from legumes) (Blanco-Canqui et al., 2015). Because mulch modulates soil temperature and moisture, maintaining surface mulch is a critical adaptive strategy as many regions face drier, hotter summers with climate change (Hayhoe et al., 2007; Kaye and Quemada, 2017).

We sought to investigate the potential of reusable tarps to terminate overwintering cover crops and facilitate organic no-till cabbage production. Our objectives were to: 1) quantify the effects of tillage and tarping on cabbage weight with and without additional weed management; and 2) determine how tillage and tarping affect weed biomass, community composition, and diversity. We conducted field experiments over two years in three fields in central Maine, USA. To shed light on the possible mechanisms for observed effects, we quantified cover crop biomass in all three fields, and monitored soil moisture and temperature in one field.

Materials & Methods

Experiment site

We conducted field experiments in 2017–2018 (Year 1) and 2018–2019 (Year 2) at a certified organic farm in Turner, Maine, USA (44° 19′ 27″ N, 70° 11′ 22″ W). In Year 1, we conducted the same experiment in two fields that have different soil characteristics and weed communities. The “Road” field is classified as Merrimac fine sandy loam (Sandy, mixed, mesic Typic Dystrudept), and the “River” field is classified as a Ninigret fine sandy loam (Coarse-loamy over sandy or sandy-skeletal, mixed, active, mesic Aquic Dystrudepts), but the absence of redoximorphic features above 1 m indicate it is well or excessively well drained and is more likely Agawam fine sandy loam (Coarse-loamy over sandy or sandy-skeletal, mixed, active, mesic Typic Dystrudepts). In Year 2, we conducted the experiment on an adjacent section of the River field. Both fields had a history of poultry litter application resulting in soil pH of 7.1 and 6.9 in the Road and River fields, respectively and phosphorus and calcium soil test values considered “above optimum” by the University of Maine Soil Testing Lab. Other macronutrients were considered “low-medium”. Soil organic matter was 4.1 and 2.8 % in the Road and River fields, respectively. Both fields had a history of vegetable production with tillage and cover crops.

Treatment structure and experimental design

Treatment structure was a 2x2x2 factorial with tillage (No-till vs. Till), tarp (No-tarp vs. Tarp), and weed management (unweeded vs. weeded) as the factors. Main plots were the four tillage by tarp combinations (No-till/Tarp; No-Till/No-tarp; Till/Tarp; Till/No-tarp), organized in a randomized complete block design. Weed management was imposed as a split-plot within these treatments. In Year 1, each field had four blocks and in year two, the field had five blocks. Main plots were 12 x 3m, and sub-plots were 6 x 3m. The factorial treatment structure allowed us to look for main effects and interactions between tillage, tarping, and weeding. Additional details about how these treatments were managed is included in the field activities section.

Weather data

Weather data were downloaded from weather station USC00178817 (Turner, Maine). Growing degree days were calculated using the following equation:

$$GDD = \frac{T_{\max} + T_{min}}{2} - T_{base}$$

Where T_{max} is the maximum daily temperature, T_{min} is the minimum daily temperature, and T_{base} is 4°C; mean temperatures below T_{base} are considered zero. Cumulative GDD for the cover crop growing seasons were calculated as the summation of daily GDD starting on the day of cover crop seeding until the cover crop biomass was harvested (Table 2.1). Cumulative GDD for the tarping period and cabbage growth period were similarly calculated from the day of tarp application until the day of tarp removal and from the day of cabbage transplanting until the day of cabbage harvest. Four degrees C is a common base temperature for winter rye and hairy vetch (Teasdale et al., 2004; Mirsky et al., 2009), and there is little data on the appropriate base temperature for cabbage. We have kept this base temperature for all periods of the cropping sequence to allow for comparison with a common unit.

Field activities

Dates for field activities are presented in Table 2.1. Fields were rototilled prior to seeding cover crops. In Year 1, cereal rye (*Secale cereale* L., VNS) and hairy vetch (*Vicia villosa* Roth, VNS) both from Johnny's Seeds (Winslow, ME) were mixed and seeded in the fall at a rate of 50 and 13 kg ha^{-1}, respectively, using two passes of a vacuum seeder (MaterMacc, S. Vito al Tagliamento, Italy) to create rows 15 cm apart. In Year 2, 'Aroostook' cereal rye (Albert Lea Seeds, Albert Lea, MN) was seeded with VNS hairy vetch (Johnny's Selected Seeds, Winslow, ME), at a rate of 145 and 34 kg ha^{-1}, respectively, using a Brillion 3m drop seeder (Landoll, Marysville, KS). Vetch was inoculated with *Rhizobium leguminosarum* biovar. *viceae* (Verdesian LifeSciences, Cary, NC) both years prior to seeding.

In the subsequent June, we rolled cover crops in the No-till/Tarp treatment with a disengaged rototiller prior to applying tarps in order to lay them flat without creating stubble that could puncture the tarps. We mowed cover crops in all other treatments with a sickle bar mower. Tilled plots were rototilled to approximately 12cm. In the tarped treatments, tarps were new, 4 mil (0.10 mm) low density polyethylene film (Visqueen) and were held in place with 15cm sod staples placed every 1m along the edges. To control actively growing weeds in the no tarp treatments, additional weed management was applied before transplanting cabbage. The Till/No-tarp treatment was managed in accordance with a stale seedbed practice (Boyd et al., 2006), and was lightly hoed with a stirrup hoe (Johnny's Selected Seeds, Winslow, ME). The No-Till/No-tarp treatment was managed by mowing with a push lawnmower at 10cm above the soil surface; this did not entirely terminate weeds or cover crop regrowth, but represents the limited non-chemical options (other than tarps) allowable under organic standards.

We transplanted cabbage (*Brassica oleracea* var. capitata 'Tiara'; Johnny's Selected Seeds, Winslow, ME) in all treatments in early July. This variety is a mini cabbage for high-density plantings and has a typical head weight of approximately 450–900g. Holes were established with a container dibble bar with a 15cm x 3.8cm dibble point (Forestry Suppliers Inc., Jackson, MS). Three rows of cabbages were planted per plot with 30cm in-row spacing and 46cm between-row spacing. With a typical spacing of 0.9m between beds, this is equivalent to a population of 53,930 cabbages ha^{-1}.

Because of extremely dry conditions, we applied approximately 3cm of irrigation immediately after transplanting cabbage in Year 2 using overhead sprinklers (Rain Bird

Corporation, Azusa, CA). No other irrigation was applied. We applied fertilizer approved for organic production (8-2-2, Kreher Family Farms, Clarence, NY) next to each plant without incorporation at a rate of 135 kg N ha^{-1} in the River field (both years) and 68 kg N ha^{-1} in the Road field because of delayed application and higher soil organic matter levels.

In the weeded sub-plots, we hand pulled weeds and used a hand hoe (Johnny's Selected Seeds, Winslow, ME) when necessary. In the No-till treatments, we attempted not to disturb the mulch and soil surface. To control imported cabbage worms (*Pieris rapae*), we sprayed 'Entrust' (Dow Agrosciences, Indianapolis, IN) with active ingredient Spinosad on August 10, 2017 and August 24, 2018 at the label rate.

Table 2.1: Field activities of cover crop, tarp, and cabbage production sequence.

	Road Year 1	River Year 1	River Year 2
Cover crop seeding	25 September 2016	25 September 2016	25 September 2017
Cover crop biomass harvest	3 June 2017	4 June 2017	3 June 2018
Rototill &	4 June 2017	4 June 2017	5 June 2018
apply tarps	5 June 2017	8 June 2017	5 June 2018
Remove tarps & transplant cabbage	4-5 July 2017	5-6 July 2017	1-6 July 2018
Fertilize cabbage	1 August 2017	19 July 2017	10 July 2018
Weeded (first weeding)	29 July 2017	31 July 2017	19 July 2018
Harvest cabbage	21 August 2017	31 August 2017	1 September 2018
Harvest weeds in unweeded subplots	23 August 2017	1 September 2017	7 September 2018

Cover crop biomass

To determine cover crop biomass and the rye:vetch ratio, we harvested two 0.25m^2 quadrats from each main plot by cutting stems originating within the quadrat. Rye and vetch were separated in the field and dried at 65°C for >48 hours and then weighed.

Cabbage head weights

Ten individual cabbage heads were harvested from a randomly selected section of each sub-plot (weeded or unweeded) from all three rows. In some plots, it was not possible to get all ten heads from immediately adjacent heads because of significant porcupine (*Erethizon dorsatum*) herbivory. The herbivory occurred very close to the harvest date, and we do not believe this affected competition between cabbage heads. The cabbages were harvested from the Road field in Year 1 slightly earlier than anticipated in order to avoid additional porcupine damage. Prior to measurement, outer leaves were removed and individual marketable heads were weighed fresh.

Soil moisture and temperature

In Year 2, we measured hourly soil moisture and temperature at 15cm soil depth in the weeded No-till/Tarp and Till/No-tarp treatments of three blocks using GS3 and 5TE soil temperature and capacitance moisture sensors (Meter Environment, Pullman, WA). This depth was below the depth of tillage (12cm) so that volumetric water content could be compared between Till and No-till treatments without any confounding effects of bulk density.

Weed biomass and community structure

In Year 1, we harvested weeds within a few days after cabbage harvest from a 1.2 x 1.8m quadrat in order to cover all three rows where cabbages had been growing. In Year 2, the weed biomass was substantially greater, and we harvested two 0.25m^2 quadrats from each unweeded subplot after cabbage harvest. We separated weeds to species, dried them at 65°C for >48 hours and weighed them.

Analyses

All analyses were performed within the R environment (R Core Team, 2020). We analyzed cabbage mean head weight using a linear mixed model with three-way analysis of variance (ANOVA) with the 'lme4' package (Bates et al., 2015). Tillage, tarp, and weed management were fixed effects and block was a random effect. Block was nested within field in Year 1. Field was included as a fixed effect to determine if there was a field effect or interactions. If field was not significant, it was not included in the model. Weed biomass data from the unweeded subplots were analyzed using a two-way ANOVA with tillage and tarp as fixed effects. Because of an effect of field in Year 1, fields were separated and analyzed individually. Cabbage head weight and weed biomass data were checked for assumptions of ANOVA, and all data met both normality and homoscedasticity assumptions except the cabbage weight from Year 2, which had non-normal residuals. Because it met the homoscedasticity assumption, the data were analyzed without transformation (Schmider et al., 2010). Where there was a significant interaction between factors, we present simple effect means. Means contrasts were performed with the 'emmeans' package (Lenth, 2020) using Tukey's honestly significant difference (HSD) with α=0.05.

To determine if there were differences in weed community composition and diversity resulting from tarp and tillage treatments, we calculated the Shannon diversity index and performed a permutational multivariate analysis of variance (PerMANOVA) on log(x+1) transformed biomass of species (Anderson, 2001). For both analyses, we used the 'vegan' package (Oksanen et al., 2019). PerMANOVA was performed with the Bray-Curtis distance matrix using the 'adonis' function. For visualization purposes, community data are presented as relative abundance of species representing >1% of the total weed biomass for River Years 1 and

2, and representing >5% of the total weed biomass in the Road field. All figures were created with the R ‘ggplot2’ package (Wickham, 2016).

Results

Weather

The most striking difference between years was that precipitation in May was 22% (+24mm) above average in Year 1 and 69% (-75mm) below average in Year 2 (Fig. 2.1). Both years had below average precipitation for the subsequent months of June, July, and August. Temperatures were warmer in Year 2 than Year 1, leading to greater cumulative GDD for the periods of cover crop growth, tarping, and cabbage growth (Table 2.2).

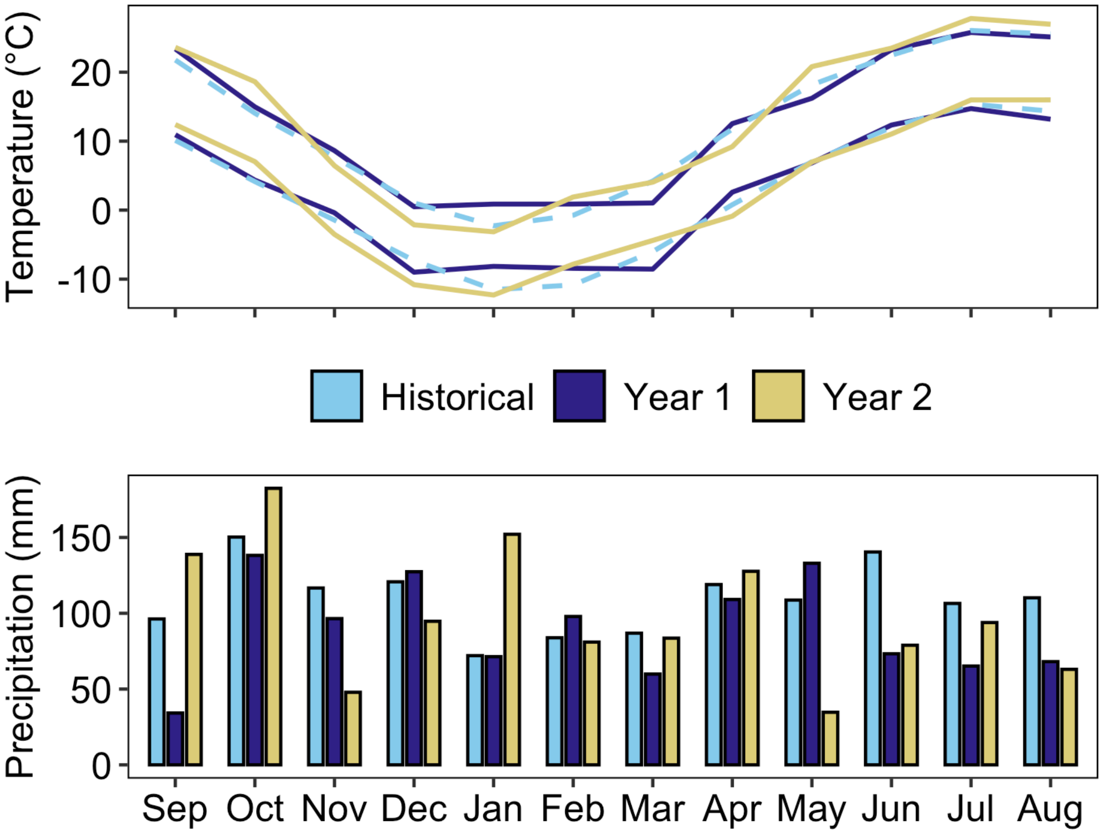

Figure 2.1: Monthly maximum and minimum temperatures (top) and monthly precipitation (bottom) in Turner, Maine. Historical data are from 2002-2016. Experiment years were 2016-2017 (Year 1) and 2017-2018 (Year 2).

Table 2.2: Cumulative growing degree days for periods of cover crop, tarping, and crop production

	Fall cover crop growth	Spring cover crop growth	Total cover crop growth	Tarping period	Cabbage growth
	Cumulative growing degree days (base 4°C)				
River (Year 1)	321	469	790	414	892
Road (Year 1)	321	461	782	428	758
River (Year 2)	421	519	940	441	994

Cover crop biomass

Cover crop biomass at the time of termination ranged from 2.8 to 4.5 Mg ha^{-1} and was dominated by rye in all fields (Table 2.3). The proportion of vetch in all fields was low, comprising less than 20% of the total biomass. The River and Road fields in Year 1 had different total biomass (p=0.002) and rye:vetch proportion, despite identical seeding methods and weather.

Table 2.3: Cover crop biomass of winter rye-hairy vetch biculture. Means with standard deviation in parentheses. Year 1 had four replications per field and Year 2 had five.

	Total biomass	Rye biomass	Vetch biomass
Field		Mg ha^{-1}	
River (Year 1)	4.5 (0.77)	4.1 (0.80)	0.44 (0.12)
Road (Year 1)	3.3 (0.40)	2.7 (0.53)	0.64 (0.23)
River (Year 2)	2.8 (0.51)	2.3 (0.41)	0.50 (0.18)

Cabbage head weight

In both years, individual cabbage heads in the highest yielding treatments were in the size range specified by the seed company for this variety (450–900g) (Fig. 2.2). In both years, multiple interactions precluded an analysis of the main effects of tillage, tarping, and weeding (Objectives 1 & 2). In Year 1, there was no effect of field on mean cabbage weight, even though there was a ten day and >130 GDD difference between cabbage harvest dates. Therefore, cabbage data from the two fields in Year 1 were analyzed together. Treatment effects in Year 2 differed from Year 1 and were analyzed separately.

Within the weeded subplots, mean cabbage weight in the No-till/Tarp treatment was either greater than (Year 1) or equal to (Year 2) all other treatments. The No-Till/No-tarp treatment, on the other hand, was consistently the lowest yielding treatment, producing cabbages that were not marketable size (Year 1) or were not harvestable (Year 2). It should be noted, however, that the weed management practices in No-Till/No-tarp (e.g. mowing prior to cabbage transplanting and subsequent hand weeding) did not keep the plots free of weeds.

The effect of weeding on mean cabbage weight was significant in all treatments in both years; however, the magnitude of the weeding effect was highly variable. In Year 1, the weeding effect was greatest in Till/No-tarp, where weeding more than doubled the mean cabbage weight. The effect was much smaller in the tarped treatments. Weeding increased cabbage weight in No-till/Tarp, but the mean cabbage weight in the unweeded No-till/Tarp was still equal or greater than all other treatments—even weeded ones. The effects of weeding were more pronounced in Year 2, in which cabbage weights in all the unweeded treatments were <50% of their weeded counterparts. All of the unweeded treatments had mean cabbage weights <300g. Cabbages in the unweeded No-Till/No-tarp treatment did not form heads and could not be harvested.

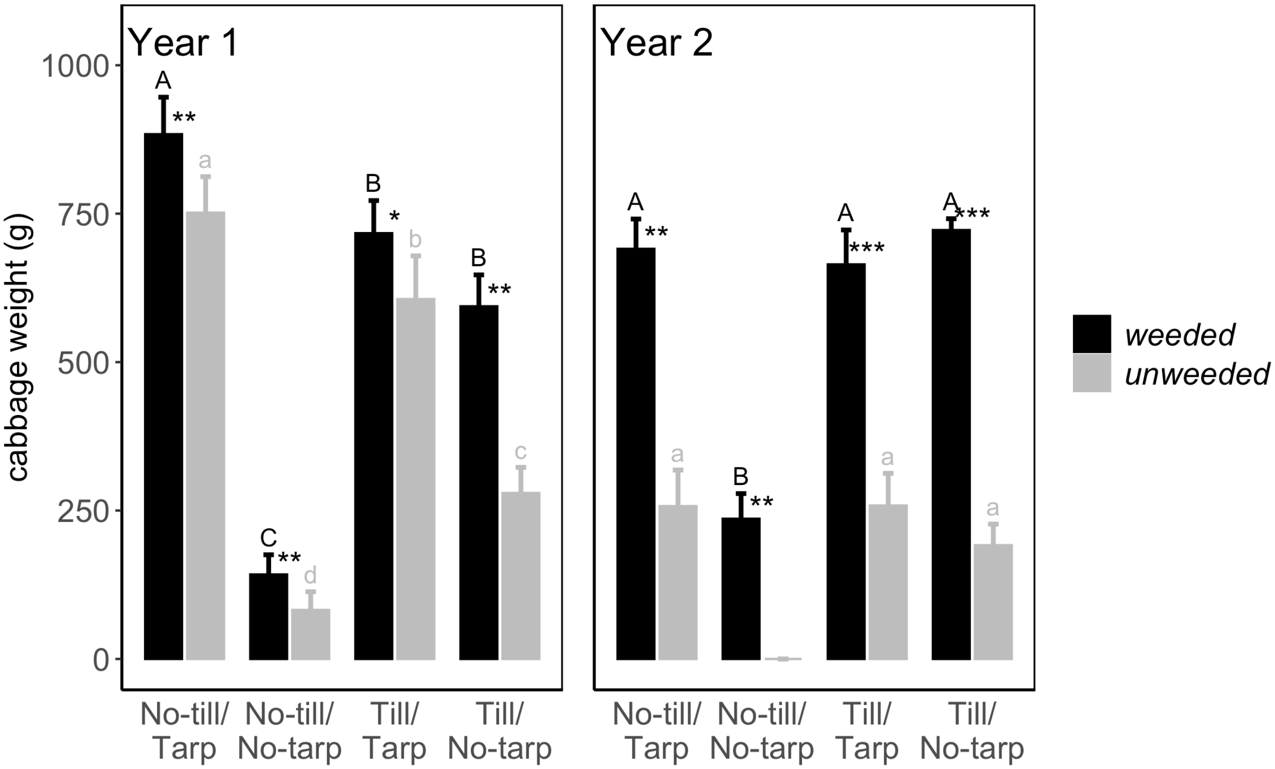

Figure 2.2: Cabbage mean head weight from two years in Turner, ME. Year 1 had two fields, which were pooled (n=8). Year 2 had one field (n=5). All plots had a winter rye-hairy vetch cover crop prior to tillage and tarping treatments. Sub-plots of each tillage x tarp combination were weeded. Error bars are standard error of the mean. Stars indicate significance between the weeded and unweeded subplots within each tillage x tarp treatment combination. Upper case letters indicate differences between the weeded treatments within each year, and lower case letters indicate differences between the unweeded treatments within each year. Means with a common letter are not different.

Soil moisture and temperature

Soil temperature in Year 2 was higher in the No-till/Tarp treatment than the Till/No-tarp treatment during the period of tarping/stale seedbedding; however, temperatures during the cabbage growth period were similar between the two treatments (Figs. 2.3a and 2.3b). The efficacy of tarps at maintaining moisture by excluding precipitation and limiting evaporation is evident from the stability of soil moisture in the No-till/Tarp treatment compared to the fluctuating soil moisture levels in the Till/No-tarp treatment (Fig. 2.3c). Soil moisture in the two treatments quickly converged after tarp removal when we irrigated once and then during subsequent precipitation events (Fig. 2.3d). In the middle of the cabbage growing season, the No-till/Tarp treatment (which no longer had a tarp on it but retained some surface mulch) maintained slightly higher soil moisture after precipitation events than the Till/no-tarp.

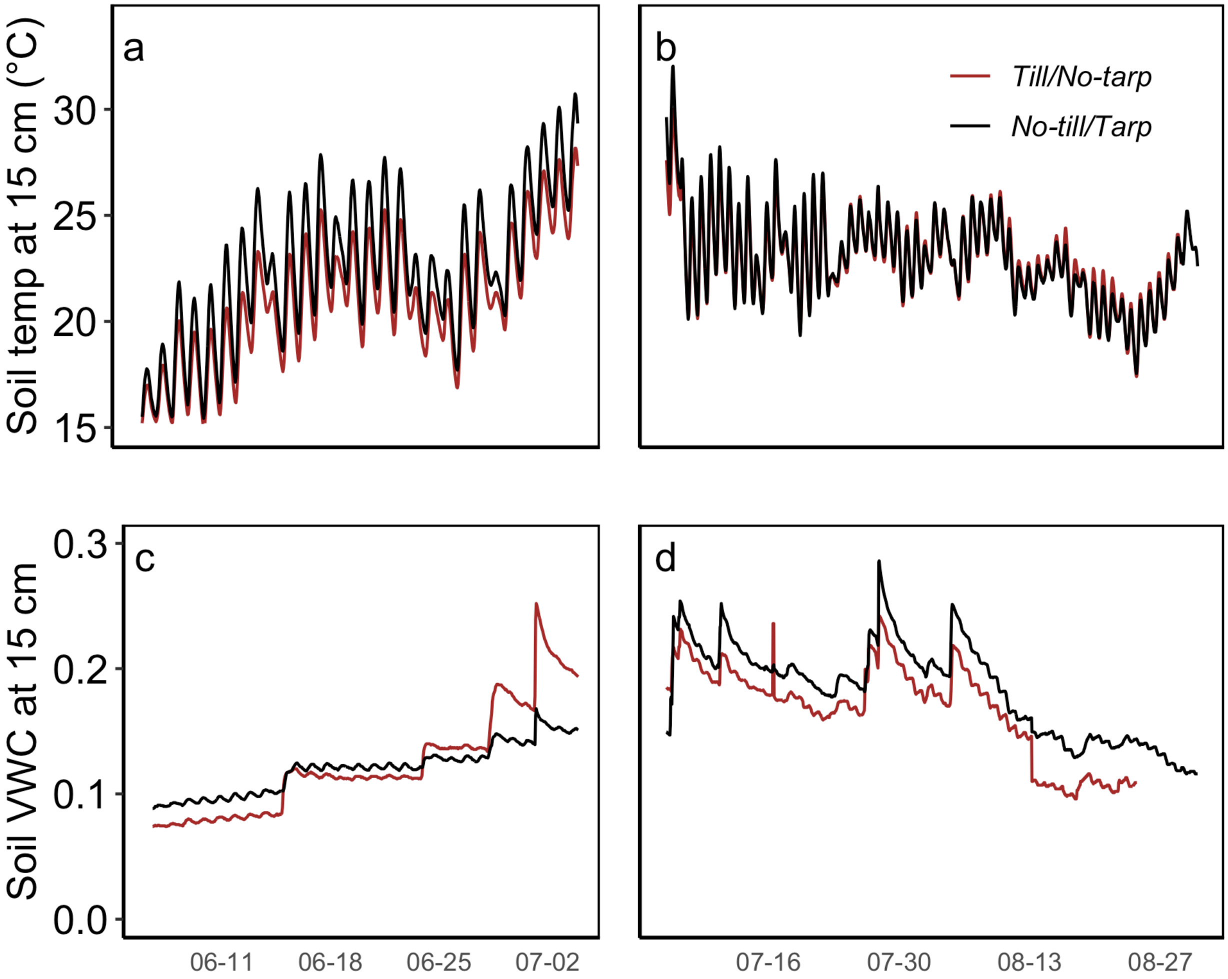

Figure 2.3: Soil temperature and volumetric water content (VWC) during the period of tarping/stale seedbedding (a & c) and cabbage growth (b & d) in Year 2. The "Till/No-tarp" treatment was a stale seedbed. The tarp was removed for the period of cabbage growth in the "No-till/Tarp" treatment and cover crop residue remained on the soil surface. Lines are means of three replications.

Weed biomass and communities

Tarping, but not tillage, reduced weed biomass (Fig. 2.4, Obj. 2). This effect was significant in both fields in Year 1, although the magnitude of the effect varied between the River and Road fields. In both fields, tarping reduced weed biomass by more than half. In Year 2, the effect of tarping was marginal (p=0.08) and weed biomass was higher across all treatments than Year 1. The negative relationship between weed biomass and mean cabbage weight was strong in 2017 (R^2=0.56, p=<0.0001), but weaker in 2018 (R^2=0.20, p=0.012).

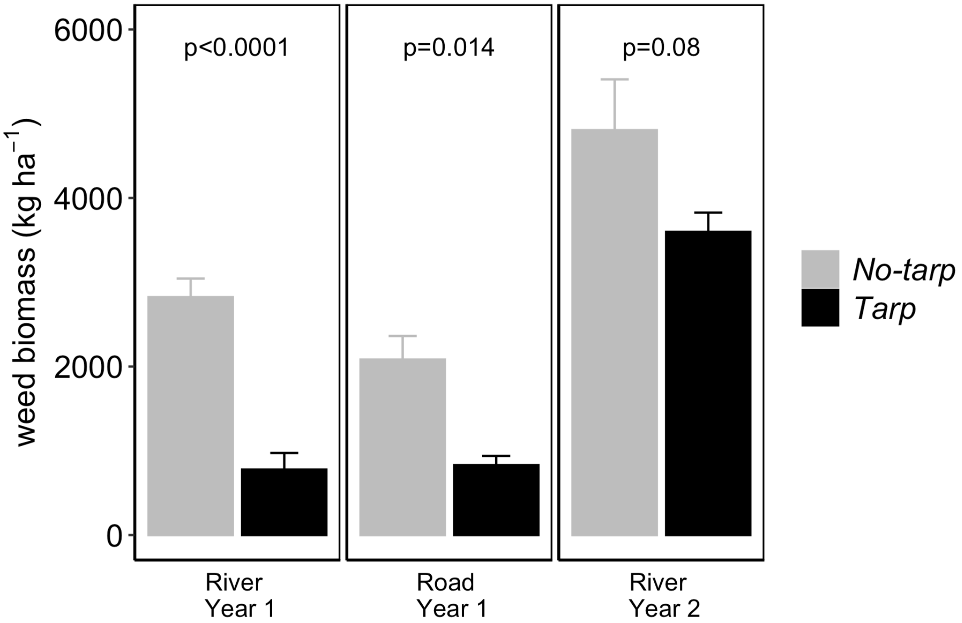

Figure 2.4: Weed biomass in unweeded subplots after cabbage harvest. Means of Tarp and No-tarp treatments include both No-till and Till. *P* values are presented for each field for the main effect of tarping. Error bars are standard error of the mean (n=8 for Year 1 fields and n=10 for Year 2 River field).

Tarp and tillage treatments led to different weed community composition (Fig. 2.5). The PerMANOVA indicated a significant tarp*tillage*field effect on weed communities in Year 1 (p=0.004). The tarp*tillage interaction remained significant in the Road field (p=0.001) and the River field (p=0.011). These community effects also manifested in differences in the Shannon diversity index (Table 2.4). In Year 1, diversity was lowest in the No-till/Tarp plots and highest in the No-Till/No-tarp plots. In Year 2, PerMANOVA indicated a significant effect of tarp (p=0.001) on weed community composition; however, there were no differences in diversity between treatments. Redroot pigweed (*Amaranthus retrofexus L.)* and common lambsquarters (*Chenopodium album L.)* were the only weed species occurring in all three fields at >1% biomass, while large crabgrass (*Digitaria sanguinalis (L.) Scop.*) was common in both years of the River field, especially Year 2.

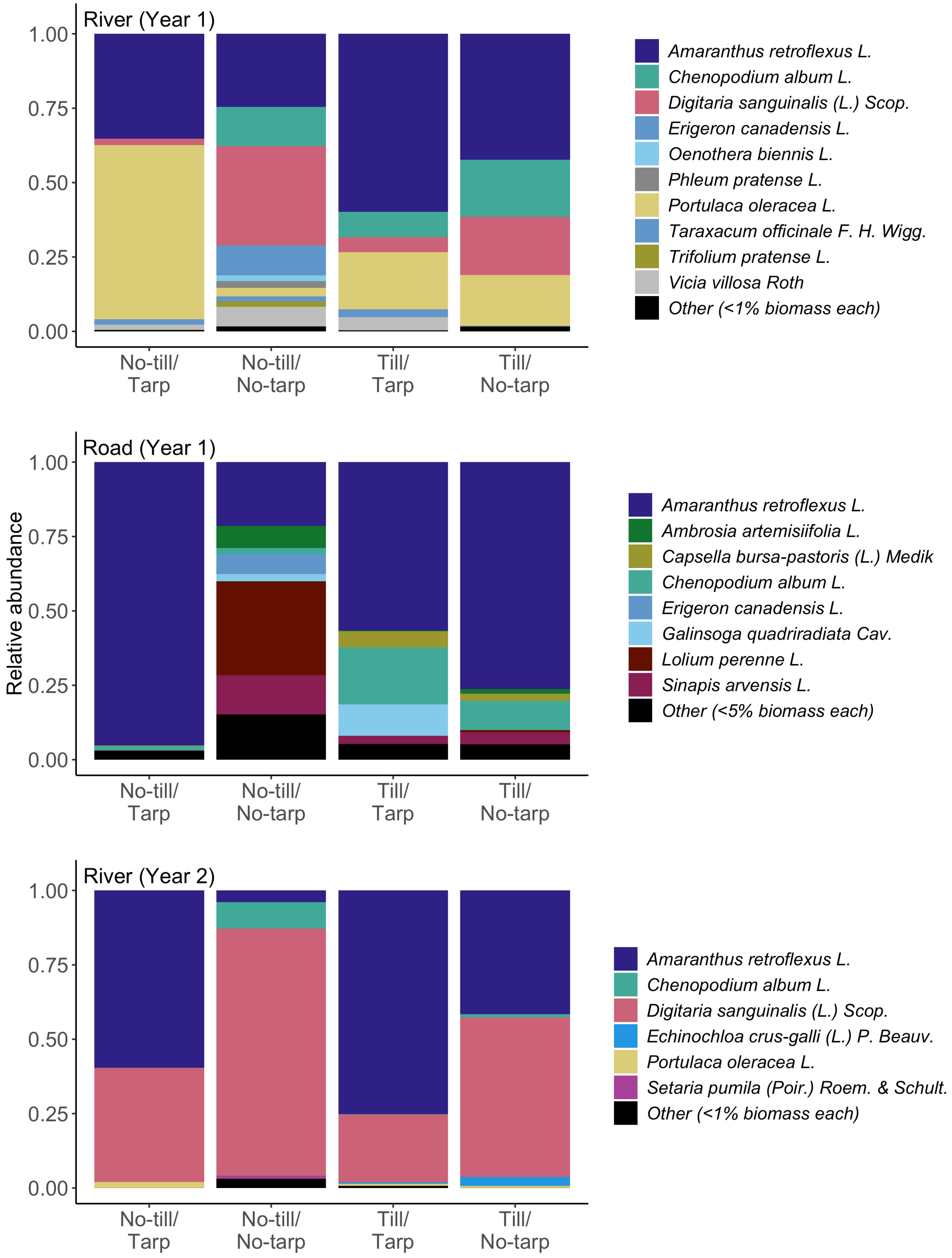

Figure 2.5: Relative abundance of weed species after cabbage harvest in unweeded subplots. Year 1 had four replications per field and Year 2 had five.

Table 2.4: Shannon diversity index of weed community after cabbage harvest. Within a field, means with different letters are significantly different (Tukey's HSD, α=0.05). Year 1 fields had four replications and Year 2 had five.

Field	No-till/Tarp	No-till/No-tarp	Till/Tarp	Till/No-tarp
River (Year 1)	0.77 b	1.5 a	1.0 b	1.0 b
Road (Year 1)	0.24 c	1.6 a	0.90 b	0.78 b
River (Year 2)	0.70	0.48	0.54	0.76

Discussion

Cover crop performance

Cover crop biomass in our experiment was well below the levels required to provide adequate weed suppression via cover crop mulch alone. In southern latitudes, 8 Mg ha^{-1} has been determined as the threshold for cover crop mulch based systems (Reberg-Horton et al., 2012; Mirsky et al., 2013). Some authors have suggested that lower biomass levels (e.g. 5–6 Mg ha^{-1}) may be sufficient in northern latitudes (Wallace et al., 2017), but data are lacking to develop thresholds. The relatively low biomass in our experiment was likely a result of low GDDs, as well as extremely low precipitation in May in Year 2. While there is potential to increase biomass through earlier fall seeding, delayed spring termination, and perhaps higher seeding densities (Boyd et al., 2009; Mirsky et al., 2011), our results highlight the challenges in relying on cover crop biomass alone to provide adequate weed suppression in northern latitudes. Our results also highlight the role of edaphic factors in determining cover crop biomass, evidenced by the difference in biomass between the closely situated Road and River fields in Year 1.

Although we did not measure N content of cover crops, low hairy vetch proportion in all fields indicates that the N contribution was likely low (e.g. <25 kg ha^{-1} assuming 4% N). To provide significant N fertilizer replacement value, alternative management to increase hairy vetch biomass will likely be necessary. Hairy vetch matures later than winter rye and continues to accumulate biomass and fix N after winter rye has reached peak biomass (Mirsky et al., 2017; Thapa et al., 2018). This suggests that delayed termination in spring may be a strategy worth pursuing to increase the N contribution from cover crops in this system. In regions where P applications are restricted, higher contributions of biologically fixed N from legume cover crops is an effective strategy to meet crop N requirements with minimal external inputs (Ackroyd et al., 2019).

Cabbage weight

Tillage and tarping

Equal (Year 2) and greater (Year 1) mean cabbage weights for No-till/Tarp compared to the more traditional Till/No-tarp (i.e. stale seedbed) show that tillage is not necessary and sometimes disadvantageous to produce the highest cabbage yields. Tarps were essential to make no-till viable, evidenced by dramatic differences in mean cabbage weight between No-till/Tarp and No-Till/No-tarp. Tarps alleviated some of the yield limitations of cabbage growth identified in previous cover crop based no-till research by completely terminating cover crops and existing weeds and providing additional weed suppression (Fig. 1.4). Other yield limiting factors in previous research, including preemptive competition from cover crops and low N availability—even when fertilizer in excess of recommended rates has been applied— appear not to have been constraints in the No-till/Tarp system (Mochizuki et al., 2008; Leavitt et al., 2011; Hefner et al., 2020a).

Tarps affect soil temperature and moisture dynamics in two key ways that may explain why N availability appears not to have been a yield limiting factor in No-till/Tarp. Tarps exclude precipitation, and therefore leaching losses when they are in place are minimal. At multiple sites, an accumulation of soil nitrate that increased with tarp duration was observed when tarps were placed over a winterkilled oat (*Avena sativa* L.) cover crop (Rylander et al., 2020a). Additionally, higher temperatures—though not in excess of 30°C— in No-till/Tarp compared to Till/No-tarp in Year 2 (Fig. 3) may lead to greater N mineralization under tarps, provided there is sufficient moisture (Cassman and Munns, 1980). However, very little information exists about how tarping affects microbial function, and this speculation needs further study. It should also be noted that the effects of tarping on soil temperature are complex and the presence of large amounts of mulch under tarps can limit tarp-soil contact, thereby reducing soil temperatures in some conditions (Lounsbury et al., 2020).

Perhaps more important than the evidence that No-till/Tarp can overcome some of the yield limitations of previous cover crop mulch based no-till is that No-till/Tarp can provide a yield advantage over tilled systems under certain conditions. We speculate that the higher mean cabbage weight of No-till/Tarp compared to all other treatments in Year 1 was in part a result of moisture conservation from cover crop mulch. Cover crop mulch prevents the loss of moisture under droughty conditions by reducing evaporation (Teasdale and Mohler, 1993). We speculate that this effect may not have factored into mean cabbage weights in Year 2 because of lower cover crop biomass levels and different precipitation patterns. Precipitation in the month of July when cabbages had just been transplanted was substantially below average in Year 1, but it was close to the norm in Year 2 (Fig. 1). This is important because it highlights that current production systems may not be optimized for a changing climate.

Our decision not to have a bare soil control makes it difficult to assess whether preemptive competition from cover crops limited cabbage yields. We acknowledge that our Till/No-tarp practice, although a form of stale-seedbedding, is not "standard," but mean cabbage weights in the highest yielding treatments of our experiment were within the mid to upper range specified by the seed company. Furthermore, they were produced in less than the 63 days to maturity specified by the seed company, and in drier than average summers. This suggests that the cabbage weights in our treatments were normal—not dramatically reduced as was the case for Hefner et al. (2020) who observed 68-100% cabbage yield reductions following roll-crimped cover crops compared to tilled bare soil controls. The four-week period of either tarping or stale seedbedding between cover crop termination and cabbage transplanting may have reduced risks of preemptive competition from cover crops.

It should also be noted that inherent and management-induced soil properties play an important role in the success of no-till planted vegetables. Identical management practices can have highly site-specific effects, especially when soil compaction is present (Lounsbury and Weil, 2015). Cabbage and many other vegetables are sensitive to soil compaction and the associated condition of saturated soils (Wolfe et al., 1995; Mochizuki et al., 2007). The soils in this study were not susceptible to these conditions.

Weeds

Tarping was very effective at reducing weed biomass in Year 1, likely contributing to the small difference in cabbage mean weight between weeded and unweeded subplots in tarped treatments. In contrast, the large difference between weeded and unweeded subplots in Till/Tarp highlight the impact weeds can have on yields under more standard management practices. The practical implications of this are that tarping may give farmers more flexibility about when additional weed control is performed without risking significant yield losses. This is a significant advantage during the growing season when farmers face multiple demands on their time (Schonbeck, 1999). It should be noted, however, that we did not quantify weeding time. While it is likely that most farmers using tarps are working on a small scale without mechanization, weeding with cover crop residue requires different tools than weeding bare soil and may affect the amount of labor required.

Tarping was less effective at weed suppression in Year 2, however. We think that this is in large part because of the low soil moisture when tarps were applied (Fig. 3). We applied tarps immediately after a precipitation event in Year 2, but the lack of precipitation in May likely led to a soil water deficit that a single precipitation event was unable to overcome. The efficacy of tarping for weed control relies on adequate soil moisture, which may induce fatal germination of weed seeds (Birthisel and Gallandt, 2019). In dry years, irrigation before tarping may be necessary to make this system most effective. The timing of weeding differed somewhat between the two years, but is an unlikely explanation for the differences observed. Weed management was consistent with what has been identified as necessary to minimize yield losses for cabbage (Weaver, 1984; Kołota and Chohura, 2008).

Effects of tarping on weed community composition and diversity, in addition to weed biomass, indicate that tarping can act as a strong filter on weed community assembly (Booth and Swanton, 2002; Birthisel and Gallandt, 2019). Our data suggest that while most weed species were suppressed by tarping, some are capable of "passing through" the filter, including *A. retroflexus*, which is one of the most common weeds found on organic farms in New England (Smith et al., 2018). Rylander et al (2020) found that seeds of a closely related species, *A. powelli,* actually appeared to have greater survival under tarps compared to bare soil. These results indicate that farmers should be cautious about selecting for certain weed species and traits when using tarping in conjunction with no-till. Approaches to manage weed seed rain may be beneficial in the long-term, even if weeds have a only limited impacts on yields (Brown et al., 2018).

Tradeoffs of the system

Soil moisture

The No-till/Tarp system is a promising method to manage soil moisture, but it is multi-faceted. Cover crops, the resulting cover crop mulch, and tarps modulate the soil moisture regime for a subsequent cash crop via effects on transpiration, evaporation, and infiltration. In dry years, cover crops can deplete soil moisture and negatively affect availability for a subsequent crop (Unger and Vigil, 1998; Alonso-Ayuso et al., 2014). This presents farmers with a difficult decision about when to terminate cover crops if preemptive competition for soil moisture by the cover crop is a concern and irrigation is not available (Alonso-Ayuso et al., 2014). However, early termination limits the quantity of biomass and subsequent mulch, potentially limiting the beneficial effects of moisture conservation later in the season. In wet years, tarps can prevent soils from becoming saturated because they exclude precipitation and maintain soil moisture at relatively constant levels (Fig. 3). This increases flexibility around the timing of field work. Effects of the No-till/Tarp system will likely be very different in dry vs. wet years and dependent upon when major precipitation events occur (i.e. during cover crop growth, tarping, or cash crop growth).

Opportunity costs

The biggest tradeoff of the No-till/Tarp system is captured in the division of thermal units (GDDs) in the season. Thermal units are limited in northern climates and can be used for cover crop production, tarping, or cash crop production. Any activity that takes thermal units away from cash crop production can be viewed as an opportunity cost and must provide additional benefits that make up for this cost. In this system, cover crop mulch can provide weed suppression, moisture conservation, and nutrients. Additional weed suppression alleviates the labor burden at peak harvest times, but applying and removing tarps requires labor at earlier times in the growing season. Moisture conservation, as discussed, is complex but will be increasingly important in the face of climate change (Kaye and Quemada, 2017).

Although hairy vetch did not provide high biomass (and therefore N) in this experiment, the use of legume cover crops—especially in soils with high P levels—will be increasingly valuable as more states move to regulate P applications (Coale et al., 2002; Kogelmann et al., 2004). Use of hairy vetch has allowed organic farmers to use lower rates of manure-based fertilizer, thereby limiting excessive P accumulation in the mid-Atlantic (Ackroyd et al., 2019). Greater allocation of thermal units to cover crop production would allow for more hairy vetch biomass production.

Further refinements of the No-till/Tarp system include developing thermal models for cover crop growth, tarping period, and cash crop growth to maximize the benefits and minimize the costs with respect to thermal units. There are thermal models for some cover crops (Teasdale et al., 2004; Mirsky et al., 2009; Thapa et al., 2018) and weeds (Myers et al., 2004), but this strategy has not been employed for tarping and only to a limited extent for vegetable crop growth. Currently, many field activities and research are calendar-based such as planting dates, days to maturity of crops, and tarping durations. A move to thermal models for all components within the cropping system would allow farmers to assess tradeoffs and determine what is most effective in their unique context.

This work investigated overwintering cover crops for cabbage production, but growing a cover crop, applying a tarp for a period of days to weeks, and then planting a cash crop into the resulting cover crop mulch could be used for other cover and cash cropping sequences as well. Results from this experiment show that tarps make cover crop based no-till feasible. The production of *in situ* mulch from cover crops can reduce reliance on external inputs like compost or purchased mulch. It should be noted that there are drawbacks and concerns with using plastic, even when it is reusable, related to production, potential pollution during use, and disposal. Advances in biodegradable plastics shows promise to increase the sustainability of this practice (Sintim et al., 2020).

(No conclusion recommended for target journal)

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III. CHAPTER 3: COVER CROP TERMINATION TIME AND METHOD AFFECT WEED ABUNDANCE AND COMMUNITY DYNAMICS

Abstract:

No-till planting into a terminated cover crop mulch provides many agroecosystem benefits in the face of climate change, but non-chemical weed and cover crop management in these systems is challenging. This is especially true in regions where cover crop biomass production is limited by short growing seasons, and resulting mulch is insufficient as a sole means of weed suppression. Occultation, or the use of reusable, light-excluding tarps, can terminate cover crops and augment weed suppression, but the combined effects of cover cropping and occultation on weed communities are unknown. We investigated the effect of winter rye (*Secale cereale L.*)-hairy vetch (*Vicia villosa* Roth) cover crop termination time and termination method (occultation for ten, twenty, and thirty days vs. glyphosate) on weed biomass and weed community assembly after the critical weed free period in the absence of a growing cash crop. The effects of termination time and termination method varied between two site years in Maine and New Hampshire. Effects on weed biomass and community assembly appear to be driven by three factors: a filtering effect of mulch, which was influenced more by termination time in Maine and termination method in New Hampshire; incomplete termination and suppression of perennial weeds with short occultation periods and low levels of mulch; and the selection for weed species with different periodicities as a result of termination time and occultation duration. The combination of cover crops with occultation for subsequent no-till production is a promising strategy to reduce reliance on herbicides and/or tillage, but the strong

and variable filtering effects of this management practice must be considered as part of an integrated weed management strategy.

Introduction

Current dominant weed management strategies—herbicides and tillage— have detrimental effects on the environment, and their efficacy is threatened by the specters of herbicide resistance and climate change. Alternatives that reduce reliance on these major disturbance events, or "big hammers," as the sole mechanisms of weed management are needed (Liebman and Gallandt, 1997; MacLaren et al., 2020; Smith, 2015). Cover crop mulch-based systems, which facilitate no-till planting, incorporate ecological weed management principles and provide other agroecosystem benefits such as buffering against drought and extreme precipitation (Mirsky et al., 2012; Wells et al., 2014). Non-chemical weed management for no-till has been identified as a research priority by organic farmers (Baker and Mohler, 2015).

In cover crop mulch-based systems, weed community composition and abundance are shaped by actively growing cover crops, which alter resource availability, and by terminated cover crops, which create a physical barrier, modulate the thermal, moisture, and nutrient regimes at the soil surface, and can release allelochemicals (Mirsky et al., 2012; Nagabhushana et al., 2001; Teasdale and Mohler, 1993). In other words, cover crops act through multiple mechanisms as filters during the assembly of weed communities (Booth and Swanton, 2002). A single practice can have a range of filtering effects across a gradient of implementation (e.g., cover crop biomass levels), at different times in the growing season, and with different initial species pools, and can act within a hierarchy of other filters when combined with multiple practices (Cordeau et al., 2017a; Mirsky et al., 2011; Smith, 2006; Smith and Mortensen, 2017; Wallace et al., 2018).

Years of agronomic refinement in the mid-Atlantic and southern regions have improved the viability and reliability of mechanically-terminated cover crop mulch-based systems, although barriers to adoption remain (Mirsky et al., 2012; Reberg-Horton et al., 2012; Wallace et al., 2017). Farmers in areas with shorter growing seasons and small-scale farmers who do not have access to specialized equipment (e.g. roller-crimpers) face significant constraints in implementing these systems (Halde et al., 2017; Kornecki and Reyes, 2020). Mechanical termination, which relies on cover crop phenology, is often not feasible within the limited growing season and cover crop biomass is frequently too low to act as the sole means of weed suppression as mulch.

Light occlusion with tarps, also called occultation, is an alternative non-chemical strategy that increases flexibility in the timing of cover crop termination and augments weed suppression, thereby facilitating cover crop mulch-based no-till (Lounsbury et al., 2020)(& chapter 2). Occultation is increasingly popular on small organic farms because it is highly effective at killing extant weeds and provides more enduring weed suppression than tillage, possibly by stimulating fatal germination of weed seeds (Birthisel and Gallandt, 2019; Rylander et al., 2020a). Although occultation is effective at reducing weed abundance, its effects on the weed community are relatively unknown, especially in conjunction with high-biomass cover crops. One of the mechanisms of weed suppression by occultation is by conducting heat to the soil surface and raising temperatures, but mulch limits direct contact and conduction of heat to soil (Birthisel and Gallandt, 2019; Horowitz et al., 1983; Lounsbury et al., 2020). Understanding how management practices filter weed communities —not just how they affect weed abundance— is critical to designing robust multi-tactical approaches that minimize the negative effects of weeds on crop yields while maximizing the beneficial effects of weeds on agroecosystem function including habitat for natural enemies and improvement of soil health (MacLaren et al., 2020).

We investigated weed abundance and community dynamics in winter rye (*Secale cereale* L.)- hairy vetch (*Vicia villosa* Roth) cover crops terminated by either occultation or glyphosate across three termination times and with three occultation durations. Our objectives were to 1.) determine the effects of cover crop termination time and termination method on weed biomass after a 'critical weed-free period' of 22-25 days; 2.) characterize the filtering effects of termination time and termination method by analyzing resulting weed communities using multivariate approaches.

Materials and Methods

Site and experimental design

We conducted field experiments in 2017-2018 at River Rise Farm (RRF) in Turner, Maine (44° 19′ 27″N, 70° 11′ 22″ W) and in 2018-2019 at the University of New Hampshire's Woodman Horticultural Farm (UNH) (43° 09′ 05″ N, 70° 56′ 42″ W). The soil at RRF is classified as Merrimac fine sandy loam (Sandy, mixed, mesic Typic Dystrudept) and has a surface soil (0–15 cm) pH of 6.6 and an organic matter content of 4.9%. The soil at UNH is classified as Charlton fine sandy loam (Coarse-loamy, mixed, superactive, mesic Typic Dystrudept) and has a surface soil (0–15 cm) pH of 5.5 and an organic matter content of 3.5%. The field at RRF had been in mixed vegetables and cover crops with annual tillage for the preceding seasons and the field at UNH had been in winter rye and summer annual cover crops with annual tillage for the two years prior to initiation of the experiment.

All plots were seeded to a cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) cover crop in late September. Prior to cover crop seeding on September 25, the RRF field was rototilled in early September and again immediately before seeding. At RRF, ‘Wheeler’ rye (Moore Seed Farm, Elsie, MI) and hairy vetch (VNS, Johnny’s Selected Seeds, Winslow, ME) were seeded using a Brillion drop seeder at a rate of 115 kg ha^{-1} rye and 33 kg ha^{-1} vetch. The UNH field was moldboard plowed on September 6 and harrowed on September 19, then seeded with 112 kg ha^{-1} rye and 34 kg ha^{-1} vetch (both VNS, Johnny’s Selected Seeds, Winslow, ME) using a Kraus no-till drill on September 20, 2018, followed by a pass with a Brillion. Hairy vetch seed was inoculated with *Rhizobium leguminosarum* biovar. *viceae* (Verdesian LifeSciences, Cary, NC) at both sites prior to seeding.

The experiment was arranged as a split plot within a randomized complete block design with five replications at each site. The main plot treatments were three cover crop termination dates (T1, T2, and T3), approximately ten days apart in late spring (Table 3.1) and the sub-plot treatments were termination methods. Cover crops were rolled prior to the following termination methods: glyphosate, 10-day occultation (10d), 20-day occultation (20d), 30-day occultation. Main plots were 3m wide, with four 3 x 3m sub-plots. This design resulted in 12 treatment combinations, with five possible ‘planting dates’ for a subsequent crop (Table 3.1). These ‘planting dates’ were hypothetical, since no crop was grown in order to assess weed dynamics without the potentially confounding effects of a growing crop. In the case of glyphosate treatments, ‘planting date’ was considered 10 days after herbicide, resulting in the 10d and glyphosate treatments having the same ‘planting date.’

Table 3.1: Field activity dates for River Rise Farm (RRF) and University of New Hampshire (UNH) cover crop termination and subsequent activities in 2018 and 2019 respectively.

Termination time	Termination method	Termination date[†]	'Planting date'[±]	'critical period' sampling date
		RRF		
T1	10-day occultation	13 June	23 June	16 July
	20-day occultation	13 June	3 July	25 July
	30-day occultation	13 June	13 July	5 August
	Glyphosate	14 June	23 June	16 July
T2	10-day occultation	22 June	2 July	25 July
	20-day occultation	22 June	12 July	5 August
	30-day occultation	22 June	22 July	14 August
	Glyphosate	22 June	2 July	25 July
T3	10-day occultation	3 July	13 July	5 August
	20-day occultation	3 July	23 July	14 August
	30-day occultation	3 July	2 August	23 August
	Glyphosate	3 July	13 July	5 August
		UNH		
T1	10-day occultation	22 May	1 June	26 June
	20-day occultation	22 May	12 June	5 July
	30-day occultation	22 May	21 June	17 July
	Glyphosate	23 May	1 June	26 June
T2	10-day occultation	1 June	12 June	5 July
	20-day occultation	1 June	21 June	17 July
	30-day occultation	1 June	1 July	26 July
	Glyphosate	3 June	12 June	5 July
T3	10-day occultation	12 June	21 June	17 July
	20-day occultation	12 June	1 July	26 July
	30-day occultation	12 June	12 July	*NA
	Glyphosate	12 June	21 June	17 July

[†] Termination date is the date of tarp or herbicide application

[±] Hypothetical planting date for a cash crop; used to calculate the 'critical weed free period.'

Data collection

Weather

Weather data were downloaded from weather station USC00178817 (Turner, Maine) for RRF and USW00054794 (Madbury, New Hampshire).

Cover crop termination

We rolled cover crops prior to tarp or herbicide application. At RRF, this was done with a 1.2 m water filled lawn roller (Brinly-Hardy) pulled by a riding lawnmower and at UNH with a 3m rear-mounted roller-crimper (I & J Manufacturing, Gordonsville, PA). Glyphosate plots were sprayed within two days of rolling (Table 3.1). Glyphosate used in 2018 was isopropylamine salt (50.2%) (Roundup Weed and Grass Killer, Monsanto, St. Louis, MO) at the maximum label rate to ensure cover crop termination equal to 11.3 kg ha^{-1} acid equivalent. Glyphosate used in 2019 was isopropylamine salt (40.1%) at a 2% solution label rate equal to 12.2 kg ha^{-1} acid equivalent (Makaze, Loveland Products, Greeley, CO). For the tarp treatments, we used new 6 mil (0.15mm) black on white “silage” (low density polyethylene) tarps with the black side up. Tarps were secured using 15 cm sod staples placed approximately every meter along the edges.

Cover crop quantity and quality at termination

To assess cover crop biomass and C:N, we harvested one 0.25m^2 quadrat from each sub-plot plot a maximum of three days prior to each termination date on June 10, June 21, and July 1 at RRF and May 21, May 31, and June 10 at UNH. All stems originating within the quadrat were clipped at the ground level. Rye, vetch, and weeds were separated and dried at 65° C. A subsample of rye and vetch from each plot was ground to pass a 0.841mm sieve with a Wiley Mill and then homogenized using a cell disrupter (Mini-Beadbeater96, BioSpec Products, Bartlesville, OK). These samples were analyzed for total carbon (C) and nitrogen (N) using a Primacs SNC-100-IC TOC/TN analyzer (Skalar, The Netherlands) or a Costech C/H/N/S Elemental Analyzer (Costech, Valencia, CA) (separated by block). The C:N ratio of the mixture was determined using the C and N concentrations and mass of each species to calculate a weighted average for the cover crop mixture.

Temperatures/Decomposition degree days

In order to determine how our treatments affected soil temperatures, we placed pendant temperature sensors (HOBO MX2201, Onset Computer Corporation, Bourne, MA) below cover crop mulch directly on the soil surface in the glyphosate and 10d treatments. These sensors logged temperature hourly. Means of the hourly temperatures for each treatment were plotted. Within each plot, hourly temperatures above 9°C, which is a base temperature for many annual weed species (Myers et al., 2004), were summed to quantify cumulative decomposition degree hours (DDH), and the means for each treatment were calculated.

Weed biomass and mulch remaining after the critical weed-free period

We harvested weeds and cover crop mulch remaining on the soil surface 22-25 days after 'planting date' (Table 3.1). This timing was intended to approximate the critical weed-free period for many crops, although this is highly context-dependent (Knezevic et al., 2002). We harvested weeds from two 0.25 m^{-2} quadrats per plot by cutting them at the soil surface. We then separated weeds by species (Uva et al., 1997). Cover crop regrowth occurred in some treatments at UNH, which was harvested and is reported and discussed in Chapter 4. We then cut the residue around the interior edge of each quadrat using a knife, and remaining (dead) cover crop stems at the soil surface. Both weeds and mulch were dried at 65°C for >48 hours and then weighed. Some soil contamination of mulch was visible and inevitable, but this method is a coarse estimate of mulch remaining in the field that previously illuminated differences between treatments (Lounsbury et al., 2020).

Analyses

All analyses were performed within the R environment (R Core Team, 2020). We used linear mixed models to analyze weed biomass using the "lme4" package with termination time and termination method as fixed factors and block as a random factor and Type III sums of squares (Bates et al., 2015). Weed biomass after the critical weed-free period did not meet the homoscedasticity assumption of analysis of variance (ANOVA) and was ln(x+1) transformed prior to analysis. Cover crop regrowth was not included as weed biomass in these analyses. Analyses were performed within individual sites because of interactions. P values were calculated from the models with the 'lmerTest' package (Kuznetsova et al., 2017) and means comparisons were assessed using Tukey's multiple comparison test with the "emmeans" package in R (α=0.05) (Lenth, 2020). Marginal (fixed effects only) and conditional (fixed and random effects) R^2 values for the ANOVA models were calculated using the 'MuMIn' package (Barton, 2020). To determine if the relationships between mulch and weed biomass differed between treatments, we performed an analysis of covariance (ANCOVA) in which we tested if the slopes of the regression lines differed.

Multivariate analyses were performed on log (x+1)-transformed weed biomass. We used permutational multivariate analysis of variance (PerMANOVA) with a Bray-Curtis matrix of distance coefficients to determine if communities differed between termination time and termination method, and their interaction. P values were calculated with 999 permutations using the 'adonis' function in the 'vegan' package (Oksanen et al., 2019). To visualize these differences, we used principal coordinates analysis (PCoA), a multidimensional scaling method on the plot by species matrix, with all species included. In addition to the weed communities within each plot, we plotted individual species on the ordination. We fit weed biomass, mulch remaining, Shannon's diversity index (H) and species richness (S) on the plot using the 'fit' function in 'vegan.'

Because of interactions in the perMANOVA results between termination time and termination method, we performed hierarchical clustering to determine which treatments had similar weed communities (Cordeau et al., 2017a). The resulting dendrograms were plotted using 'ggplot2'(Wickham, 2016) and 'dendextend' (Galili, 2015). To test for associations between the resulting groups and weed species, we performed an indicator species analysis (ISA) (Dufrene and Legendre, 1997) with the 'labdsv' package (Roberts, 2019). Indicator values range from 0-1, with higher numbers associated with greater affinity for that group. We report only species with a p value <0.05.

All figures were created with the 'ggplot2' package (Wickham, 2016).

Results and Discussion

Two deviations from typical weather patterns during the experimental years (Tables 3.2 and 3.3) are worth noting with respect to the cover crop performance and subsequent weed dynamics we observed in this study: spring and summer (i.e. May-August) at RRF had well below average precipitation; and temperatures in May at UNH were slightly below average while temperatures in July were slightly above average. Despite delayed termination at RRF, overall cover crop biomass was lower compared to UNH (Table 3.4), perhaps because of low precipitation in May at RRF. Cover crop performance is discussed in more detail in Chapter 4.

Table 3.2: Weather in Turner, ME (RRF) for experiment year (2017-2018) and historical average (2002-2017).

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Ave. Max. Temp (°C) (exp)	23.6	18.6	6.4	-2.1	-3.1	1.9	4.1	9.2	20.8	23.5	27.8	26.9
Ave Max. Temp (°C) (hist)	21.9	14.3	7.6	0.8	-2.1	-0.6	4.0	11.8	18.0	22.5	26.0	25.5
Ave. Min. Temp (°C) (exp)	12.4	7.0	-3.5	-10.8	-12.3	-7.8	-4.4	-0.9	7.0	11.0	16.0	16.0
Ave Min. Temp (°C) (hist)	10.3	4.3	-1.6	-7.5	-11.3	-10.7	-6.2	0.9	7.0	12.0	15.3	14.3
Average daily (°C) (exp)	13.6	9.6	-0.6	-8.7	-9.1	-4.6	-3.1	0.8	9.6	13.7	17.7	17.7
Average daily (°C) (hist)	12.1	6.2	0.8	-5.0	-8.6	-8.2	-3.7	2.9	9.1	14.1	17.2	15.9
Precipitation (mm) (exp)	139	182	48	95	152	81	84	128	35	79	94	63
Precipitation (mm) (hist)	98.9	152.3	112.4	119.1	72.0	84.7	85.2	118.3	110.2	136.2	103.9	107.6

Table 3.3: Weather in Madbury, NH (UNH) for experiment year 2018-2019 (exp) and historical average (2002-2017).

	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Ave. Max. Temp (°C) (exp)	22.6	13.0	5.2	3.5	-0.1	1.7	5.6	12.8	17.1	23.3	29.0	26.9
Ave Max. Temp (°C) (hist)	22.5	15.4	9.3	3.2	0.0	1.9	6.1	13.3	18.9	23.5	26.9	26.3
Ave. Min. Temp (°C) (exp)	12.2	3.9	-2.1	-5.7	-9.5	-7.8	-5.5	2.2	6.7	11.8	16.1	14.2
Ave Min. Temp (°C) (hist)	10.4	4.4	-0.8	-5.8	-9.7	-8.7	-4.3	1.4	7.2	12.0	15.3	14.2
Average daily (°C) (exp)	17.4	8.4	1.6	-1.1	-4.8	-3.1	0.1	7.5	11.9	17.5	22.6	20.6
Average daily (°C) (hist)	16.4	9.9	4.3	-1.3	-4.8	-3.4	0.9	7.3	13.1	17.7	21.1	20.3
Precipitation (mm) (exp)	142	114	259	83	112	83	47	138	76	131	114	89
Precipitation (mm) (hist)	100	136	102	116	74	99	109	110	104	115	109	98

Table 3.4: Cover crop biomass descriptive statistics (mean +/1 standard deviation). N=5. See Chapter 4 for additional details and analysis.

	RRF			**UNH**		
	T1	T2	T3	T1	T2	T3
Cover crop biomass (Mg ha^{-1})	3.4 (0.38)	4.4 (0.43)	5.9 (0.29)	4.4 (0.84)	6.3 (1.1)	7.8 (0.87)
Rye:vetch ratio	2.1 (0.98)	2.0 (1.1)	1.2 (0.38)	7.4 (2.8)	8.9 (7.5)	2.7 (0.38)
C:N ratio	19 (1.6)	21 (4.0)	21 (2.8)	24 (1.7)	28 (2.8)	26 (3.6)

Weed abundance after the critical weed free period

Weed biomass after the 'critical weed free period' had a similar range at RRF and UNH, but followed different patterns with respect to termination time and method (Figures 3.1 and 3.2). At RRF, the highest weed biomass (195 kg ha^{-1}) was observed in T1-10d, while the lowest biomass (1.2 kg ha^{-1}) was observed in T3-glyphosate. The ANOVA model for termination time and termination method at RRF showed significant effects of both time ($p<0.0001$) and method ($p<0.0001$), with no significant interaction ($p=0.22$). The marginal R^2 for this model, or the variability explained by the fixed factors of termination time and termination method, was 0.69, showing that there were few unexplained sources of variation.

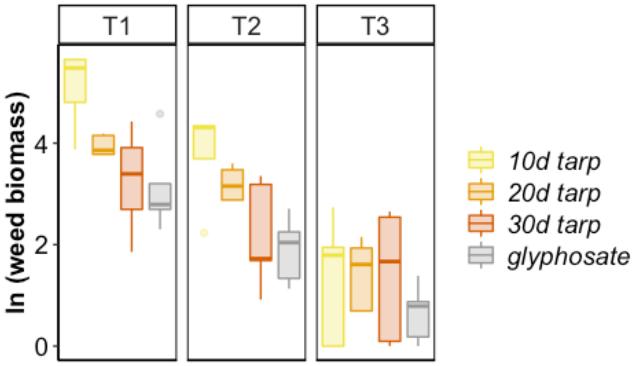

Figure 3.1: Natural log (ln) of weed biomass (kg ha^{-1}) after the 'critical weed free period' (22-25 days) following three cover crop termination dates (T1=June 12, T2=June 23, T3=July 3) and four cover crop termination methods at RRF. N=5. Boxes show the median and interquartile range.

The main effects of termination time and method at RRF are somewhat counterintuitive, as the data appear to show diminishing returns of tarp duration on weed suppression at later termination times. This may be a case in which the presence of main effects obscures important differences in simple means. For example, within each termination time, differences between termination methods are significant at T1 and T2, but not T3. The treatment structure of this experiment was designed to detect effects of termination time and method, but it should be noted that the most meaningful interpretation for farmers may be with respect to crop 'planting date', i.e., when a farmer would realistically be able to plant a crop into the terminated cover crop (Table 3.1). Multiple treatment combinations result in the same 'planting date.' For example, T1-30d and T3-10d both result in a planting date of 13 July at RRF and 21 June at UNH. Acknowledging that there are many ways to interpret the data with respect to both mechanisms and outcomes, we have presented them as boxplots.

At UNH, weed biomass did not follow the same pattern as RRF. Because of missing data from T3-30d, it was not possible to detect if there were main effects of termination time or termination method. Significant cover crop regrowth (>2000 kg ha^{-1}) in T1-10d, which was not included as weed biomass, also complicates interpretation (see Chapter 4 for more discussion of cover crop regrowth). The highest weed biomass was observed in T1-30d (168 kg ha^{-1}), and the lowest weed biomass was in T1-glyphosate (2.5 kg ha^{-1}). In T1, none of the tarping durations provided weed suppression equal to glyphosate, but T2-10d and T3-20d did ($p<0.05$). The marginal R^2 for the UNH model was 0.58. Like RRF, termination time and method accounted for well over half of the variability in weed biomass, but there was more unexplained variation at

UNH. The conditional R^2 of the model, which includes the variability explained by block, was 0.74, highlighting the spatial heterogeneity of weed biomass.

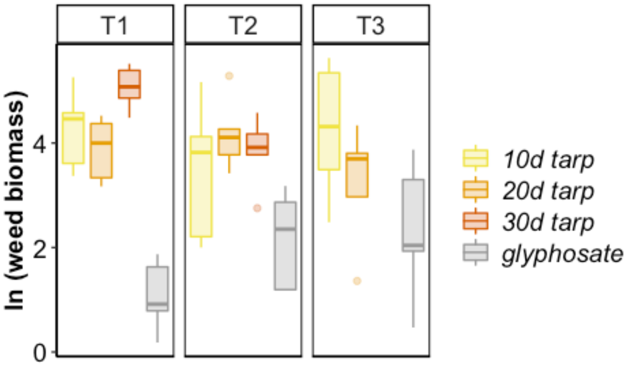

Figure 3.2: Natural log (ln) of weed biomass (kg ha^{-1}) after the 'critical weed free period' (22-25 days) following three cover crop termination dates (T1=June 12, T2=June 23, T3=July 3) and four cover crop termination methods at UNH. N=5. Boxes show the median and interquartile range. T3-30d was not harvested.

Environmental conditions at each site may explain in part why these weed biomass results were somewhat divergent. Cover crop biomass at T1 at UNH was already equal to biomass at T2 at RRF, and the cover crop at UNH had higher ratios of rye:vetch and C:N (Table 3.4). Biomass and C:N ratio are both positively correlated with weed suppression, but this relationship is not linear and varies between weed species (Pittman et al., 2020). In Virginia, Pittman et al. (2020) found that maximum suppression (80%) of *Digitaria sanguinalis* L. four weeks after termination occurred at ~5 Mg ha^{-1} cover crop biomass. Wallace et al (2018) provided a similar explanation for an absence of additional weed suppression with delayed cover crop termination in the mid-Atlantic; once a biomass threshold has been reached, delayed termination—even when accompanied by increased cover crop biomass—may not provide additional weed suppression. This highlights the need to develop cover crop biomass thresholds for maximum weed suppression along with cover crop growth models at higher latitudes in the Northeast.

In addition to mediating cover crop growth and biomass levels, environmental conditions have strong effects on weed emergence. Many common weed species have sigmoidal emergence patterns based on thermal units in which the first half plants to emerge do so over a short period, while the remaining half emerges over a much longer period. For some of the most common weed species in New England and at our sites, including large crabgrass (*Digitaria sanguinalis* L.*)* and pigweed species (*Amaranthus spp.*), the early flush occurs over a three-four week period (Myers et al., 2004). Accumulated growing degree days (base 4°C) had reached 607 by T1 at RRF, while it was only 378 by T1 at UNH. It is very likely that the period for greatest weed emergence at RRF occurred before or during occultation for many of the treatments, while at UNH a larger portion of this flush of weeds occurred after tarp removal.

Previous research conducted at the UNH site and in other sites in ME and NY indicate that weed species vary in their emergence periodicity and individual species may exhibit different emergence periodicities depending on site-specific environmental conditions (Cordeau et al. 2017a; Cordeau et al. 2017b). Weed periodicity may in part also explain the greater weed suppression by longer occultation at RRF if timing led to differences in fata germination of weed seeds. The timing of cover crop termination, therefore, has weed management implications beyond the effects mediated by changes in cover crop biomass (Mirsky et al., 2011; Wallace et al., 2018). The dry conditions at RRF in July may have lowered weed emergence, although mulch can encourage weed seed germination (Teasdale and Mohler, 1993).

Finally, it is possible that differences in the weed biomass response to termination time and termination method between the two site years is a result of variable seedbank densities.

Seedbank density can influence the effectiveness of management practices, and management practices can in turn affect the seedbank (Gallandt, 2006; Mirsky et al., 2010). Understanding the bi-directionality of this relationship is important for effectively translating research to practice (Jabbour et al., 2014). Previous work has shown that having >10,000 seeds m^{-2} is problematic for weed suppression by cover crop mulch alone, with the sheer number of weed seeds increasing opportunities for weed emergence (Mirsky et al., 2013). An observational study of 77 organic farms throughout three states including Maine and New Hampshire showed germinable weed seed density ranged from ~1,000 to over 50,000 seeds m^{-2}, with a mean of ~15,000 m^{-2} (Smith et al., 2018).

Neither weed periodicity nor seedbank density explain the stronger weed suppression from glyphosate compared to occultation that was observed at multiple termination times. For example, weed biomass was lower in glyphosate compared to 10d even though these treatments were sampled at the same time (Tables 1 and 2). Given that glyphosate has no residual activity, this could signify that glyphosate is either more effective at killing standing weeds and/or that a short period of occultation stimulates weed emergence and growth. With respect to standing weeds, perennials are more resistant to occultation than annuals, sometimes requiring long periods and/or high temperatures to eliminate (Hutchinson and Viers, 2011; Rubin and Benjamin, 1984). With respect to the idea that occultation may increase weed emergence and growth compared to glyphosate, the thermal conditions under tarps may play a role (Figure 3.3).

Occultation effects on surface soil temperatures

Occultation over cover crop mulch does not heat soil to the same extent that it does over bare soil (Lounsbury et al., 2020; Rubin and Benjamin, 1984). At T1 and T2 of both sites, occultation lowered maximum daily temperatures and increased minimum daily temperatures

(Figure 3.3). This lower daily amplitude resulted in greater cumulative thermal units for the occultation treatments. By T3, both the maximum and minimum daily temperatures in the occultation treatments were higher. Thermal conditions under occultation may have been more favorable for weed seed germination than in glyphosate treatments. Some of those germinated seeds may have then died from light deprivation (‘fatal germination’) but — especially under short durations — some may have reached the tarp removal date alive. Similarly, the short duration treatments may encourage greater weed emergence after tarp removal by warming soils and imbibing seeds, since occultation prevents evaporation and drying of the soil surface. Temperature differences may also indirectly affect weed emergence via effects on cover crop decomposition and the amount of mulch remaining.

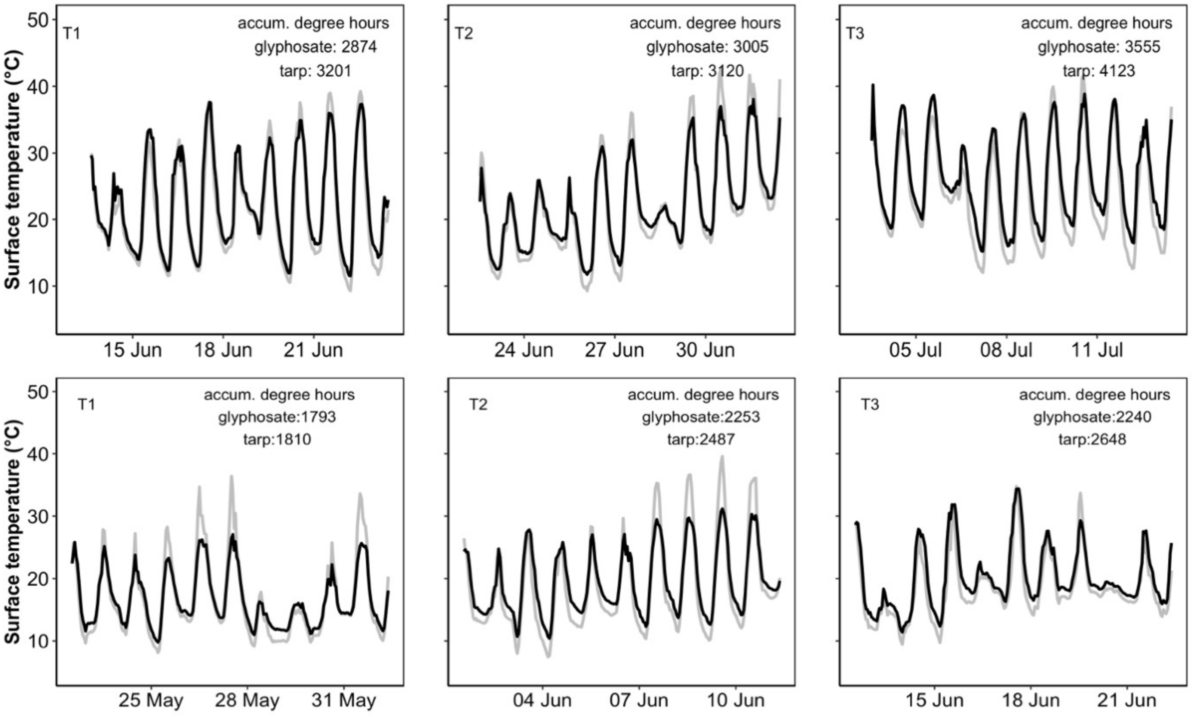

Figure 3.3: Surface soil temperatures and cumulative degree hours (base 9°C) under tarps and cover crop mulch (black lines) and glyphosate terminated mulch (gray lines) at RRF (above) and UNH (below) at three termination times.

Relationship between weed biomass and mulch after the critical weed free period

There was a negative correlation between weed biomass and mulch remaining on the soil surface at RRF and UNH, but mulch only explained 38 and 25% of the variability observed at each site respectively (Figure 3.4). There were no differences between the slopes of the regression lines of different termination times or termination methods, but there were visible groupings of the data points. At RRF, points cluster according to termination time, while at UNH the only obvious cluster is the glyphosate points.

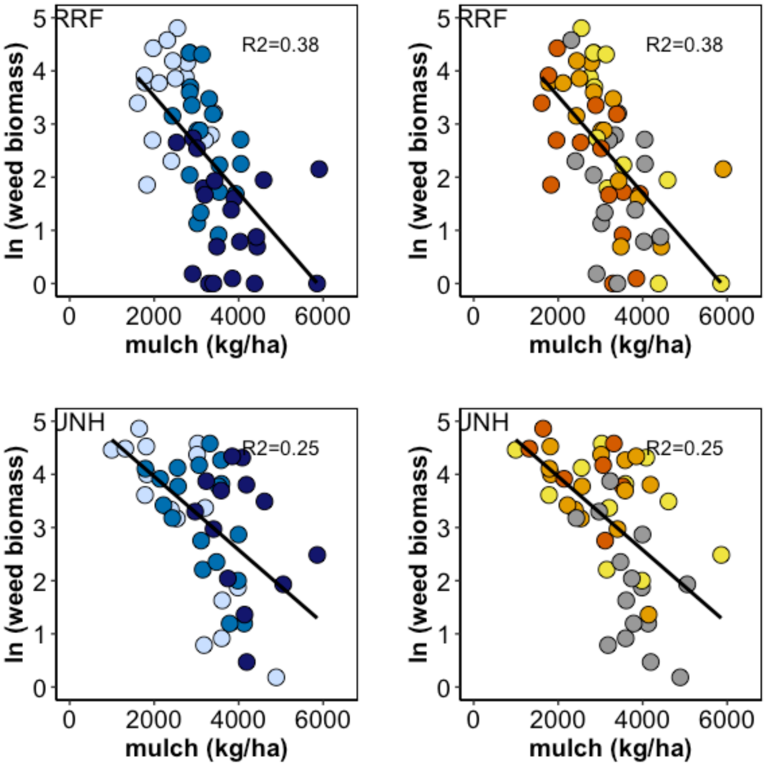

Figure 3.4: Correlations between cover crop mulch remaining on the soil surface and weed biomass sampled after the 'critical weed free period' (22-25 days) at RRF and UNH. The same data are plotted twice; on the left are color coordinated by termination time and on the right by termination method.

Weed communities as a function of termination time and method

We observed a total of 21 species at RRF and 28 species at UNH, with some overlap (Table 3.5). Like weed biomass, termination time and termination method affected weed communities differently at RRF and UNH (Figures 3.5 and 3.6). At RRF, PERMANOVA indicated that weed communities differed based on termination time (p=0.001) and termination method (p=0.001) and there was an interaction between the two factors (p=0.005). At UNH, PERMANOVA indicated only termination method affected weed community composition (p=0.001), although there was a marginal termination time by termination method interaction (p=0.10).

Table 3.5: List of all weed species from River Rise Farm and University of New Hampshire.

Species	**common name**	**BAYER code**
Acer spp.	Maple	ACERsp
Elymus repens (L.) Gould	quackgrass	AGRRE
Amaranthus retroflexus L.	redroot pigweed	AMARE
Capsella bursa-pastoris (L.) Medik.	spepherd's purse	CAPBP
Cerastium fontanum Baumg. ssp. Vulgare	mouseear chickweed	CERVU
Chenopodium album L.	common lambsquarters	CHEAL
Convolvulus arvensis L	field bindweed	CONAR
Cyperus esculentus L.	yellow nutsedge	CYPES
Dactylis glomerata L.	orchardgrass	DACGL
Digitaria ischaemum (Schreb.) Schreb. ex Muhl.	smooth crabgrass	DIGIS
Digitaria sanguinalis L.	large crabgrass	DIGSA
Echinochloa crus-galli (L.) P. Beauv.	barnyard grass	ECHCG
Erigeron annuus (L.) Pers.	Eastern annual fleabane	ERIAN
Erigeron canadensis L.	horseweed	ERICA
Galinsoga quadriradiata Cav.	hairy galinsoga	GASCI
Lamium amplexicaule L.	henbit	LAMAM
Mollugo verticillata L.	carpetweed	MOLVE
Oxalis stricta L.	yellow woodsorrel	OXAST
Panicum capillare L.	witchgrass	PANCA
Plantago major L.	broadleaf plantain	PLAMA
Poa compressa L.	Canada bluegrass	POACO
Persicaria maculosa Gray	ladys thumb	POLPE
Portulaca oleracea L.	common purslane	POROL
Rumex crispus L.	curly dock	RUMCR
Setaria pumila (Poir.) Roem. & Schult.	yellow foxtail	SETPU
Sinapis arvensis L.	wild mustard	SINAR
Stellaria media (L.) Vill.	common chickweed	STEME
Taraxacum officinale F. H. Wigg.	dandelion	TAROF
Trifolium pratense L.	red clover	TRFPR
Trifolium repens L.	white clover	TRFRE
Veronica arvensis L.	corn speedwell	VERAR
Veronica peregrina L.	purslane speedwell	VERPG
Veronica serpyllifolia L.	thymeleaf speedwell	VERSE
	unknown Brassica	UNKBR
	unknown grass	UNKGR
	unknown tree	UNK_tree
	unknown white hair	UNK_whitehari

At RRF, the centroids of the three termination times separated in ordination space primarily along the first axis, while the centroids of termination method separated primarily along the second axis (Figure 3.5). Weed communities resulting from different termination methods were comparatively more similar than termination time, with significant overlay between the 95% confidence intervals of the three occultation treatments, and some overlay between 30d and glyphosate confidence intervals. Individual species did not ordinate near the centroids of T3 or glyphosate, suggesting very few species were able to pass through filters these treatments created. Instead, most species were grouped together near T1 and 10d. The fit of mulch overlaid on the ordination was significant with an R^2 of 0.34 (p=0.001). Higher levels of mulch were correlated with T3 and glyphosate communities. Higher weed biomass, on the other hand, was correlated with T1 and 10d communities. The fit of weed biomass on the ordination was significant, with an R^2 of 0.32 (p=0.001). Shannon's diversity index (H), and species richness (S) also fit onto the ordination with R^2 of 0.35 and 0.54 respectively (p=0.001) and were oriented toward T1-10d, although in a slightly different direction from weed biomass.

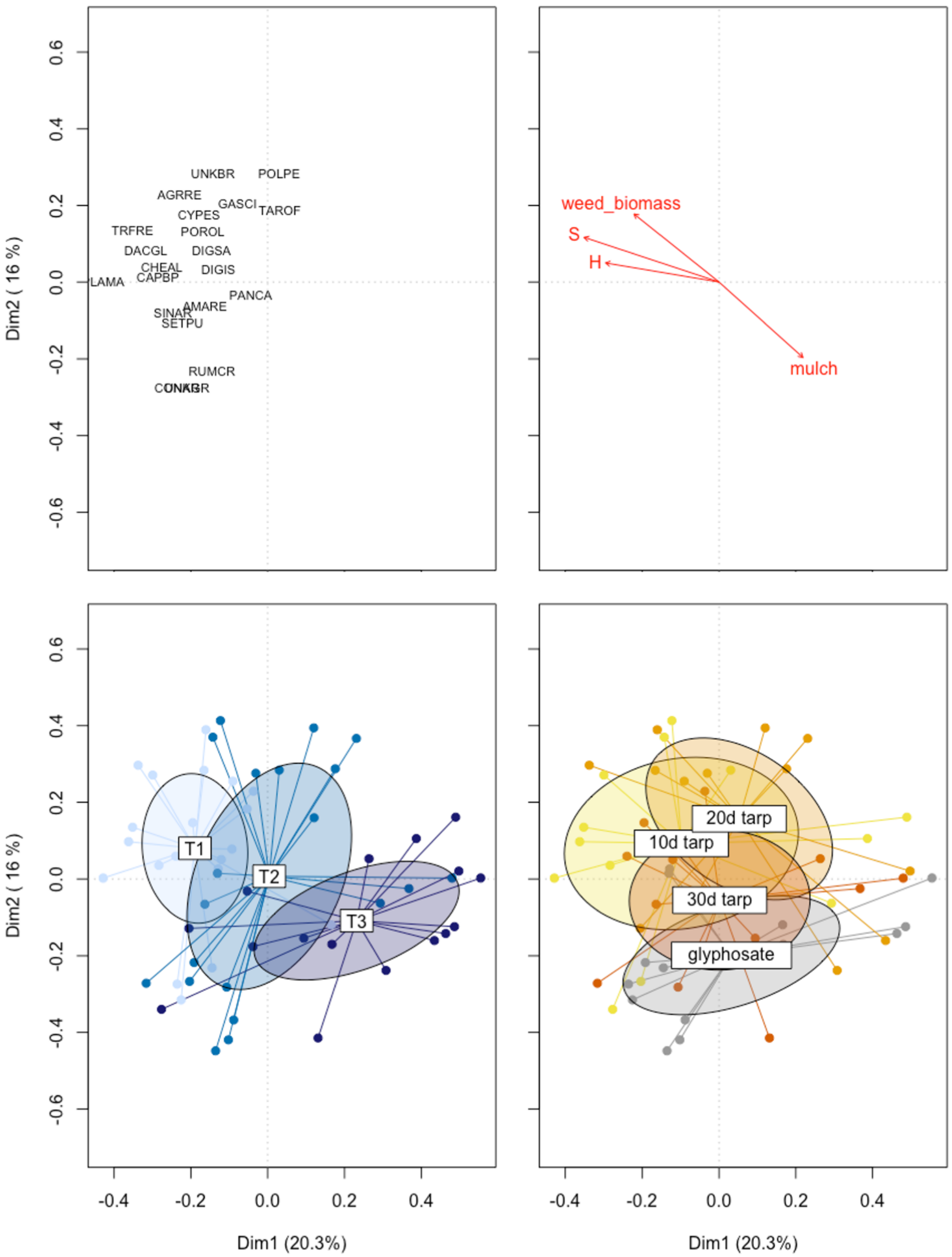

Figure 3.5: Principal coordinates analysis ordinations of weed communities at River Rise Farm. Individual species plots (upper left), correlations with other variables, and plot level groupings by termination time and termination method. Ellipses are 95% confidence intervals for the centroid of each main factor.

The absence of a difference between weed communities based on termination time at UNH is evident in the nearly overlapping centroids (Figure 3.6). The centroids for termination method, however, separate diagonally for the three occultation durations and along the second axis with glyphosate. Termination methods appear to cluster with specific weed species, with the notable absence of species clustering with the 20d communities. Given that 20d is in between the 10d and 30d treatments, this is not surprising, and highlights that there is a gradient of effects on the weed community that occurred with occultation duration at UNH. Mulch, which had an R^2 of 0.29 ($p=0.001$) and correlated with the second axis, with higher values most associated with glyphosate and lowest values associated with 30d. Unlike RRF, H was only weakly correlated to the ordination with an R^2 of 0.08 ($p=0.09$), as was S, with an R^2 of 0.17 ($p=0.009$), but like RRF, both S and H were negatively associated with glyphosate. This is visually affirmed by fewer species appearing on the ordination that overlap with the glyphosate 95% confidence interval.

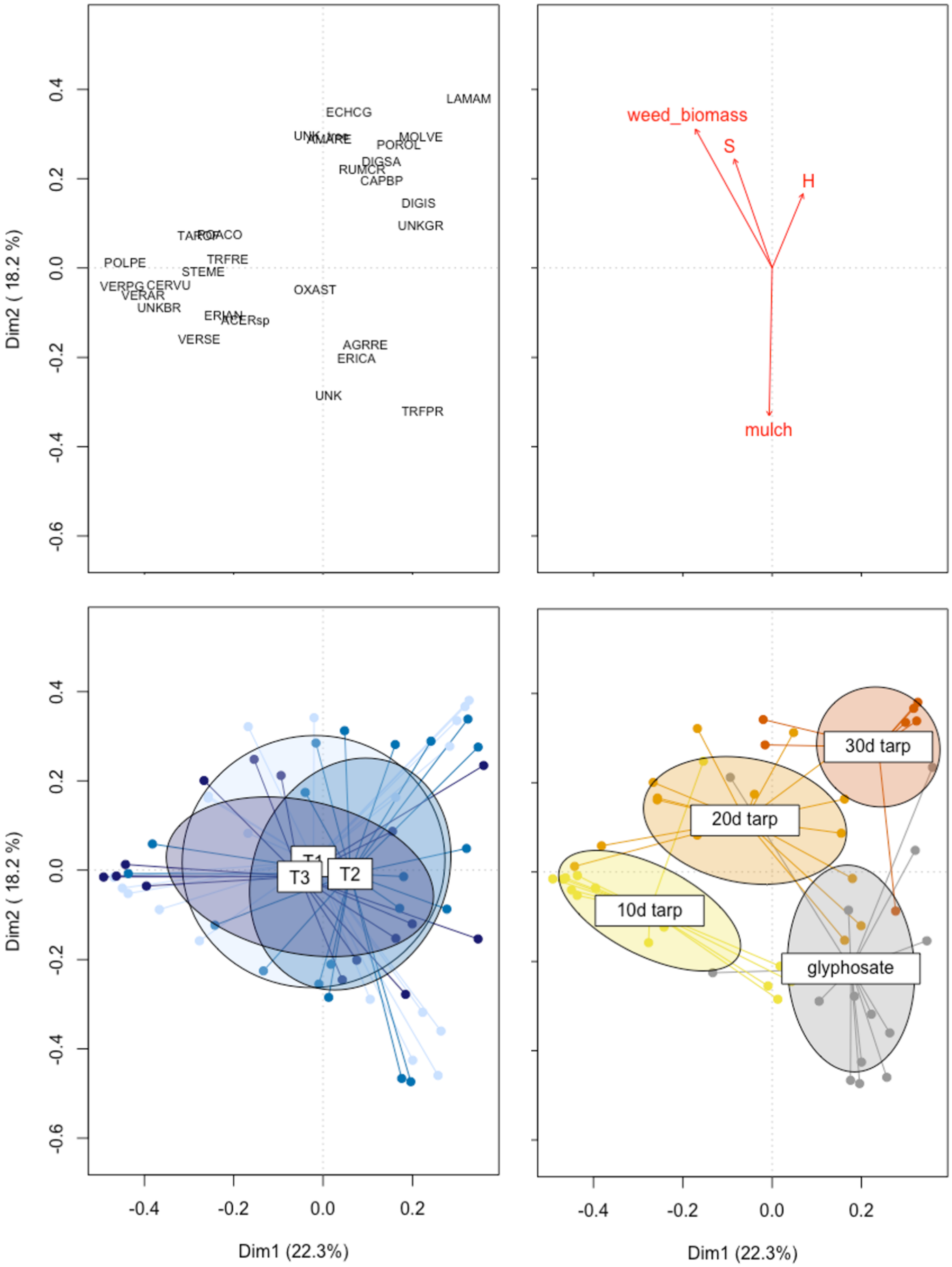

Figure 3.6: Principal coordinates analysis ordinations of weed communities at University of New Hampshire. Individual species plots (upper left), correlations with other variables, and plot level groupings by termination time and termination method. Ellipses are 95% confidence intervals for the centroid of each main factor.

Based on the differing ordinations between the two sites, mulch appears to be a strong driver of weed community composition and diversity. The filtering effect of mulch could explain the differences we observed between sites. At RRF, mulch biomass was affected more by termination time and to a lesser extent by method, while at UNH it was driven primarily by termination method. The negative association between mulch and weed diversity (H and S) at both sites indicates that fewer species are able to "pass through" the mulch filter (Booth and Swanton, 2002), although the correlation between mulch and weed diversity was much lower at UNH. Other research has found that cover crop mulch-based systems select for weeds that are not sensitive to light for germination, have overlapping periodicity with crop planting dates, and rely on leaf elongation (i.e. monocots) vs. hypocotyl elongation (i.e. dicots) (Teasdale and Mirsky, 2015; Wallace et al., 2018). Even when weeds emerge through cover crop mulch, their growth can be restricted, which is often reflected in weed biomass (Cordeau et al., 2015).

This result highlights that cover crop mulch-based systems are best as part of an integrated weed management system that includes other filters to select for contrasting traits. Unlike mechanical termination methods, which only work a certain stages of cover crop maturity, occultation is effective at any growth stage, making termination timing much more flexible. This creates an opportunity to manipulate the strength and nature of filters on weed community assembly within the same management system (i.e. cover crop plus occultation) (Smith and Mortensen, 2017). Mulch protects soil from extreme drought and precipitation (Teasdale and Mohler, 1993), but there are crops for which it is desirable to have less mulch. Occultation makes it possible to terminate cover crops without tillage, and additional research in the context of lower cover crop biomass is warranted.

Weed community hierarchical clustering and indicator species analysis

Although the ordinations provide insight into the effects of termination time and method on weed community assembly, the significant interaction in the PERMANOVA results between these factors at RRF(p=0.005), and the marginal interaction at UNH (p=0.10), suggest that the effects of termination time and method are not independent of one another. Hierarchical clustering allowed us to overcome limitations of the imposed treatment structure (Dufrene and Legendre, 1997). The resulting groups clarify the nature of the interactions between termination time and method on weed community assembly and subsequent indicator species analysis helps characterize the nature of the filters.

At RRF, weed communities from T1 ended up in three different groups, with T1-10d its own group (Figure 3.7). Weed communities from T2 were distributed between two groups, with 30d and glyphosate clustering together. All occultation treatments from T3 grouped together, and the weed community from T3-glyphosate was unique. As indicated by the PERMANOVA results and ordinations, weed community differences at UNH were mostly driven by termination method, with the exception of T3-glyphosate, which was in the same group as all the 20d treatments, but most closely related to T3-20d. The dendrogram shows that the 20d communities were more closely related to the 10d communities than they were to the 30d communities, which were the most different of all (Figure 3.8).

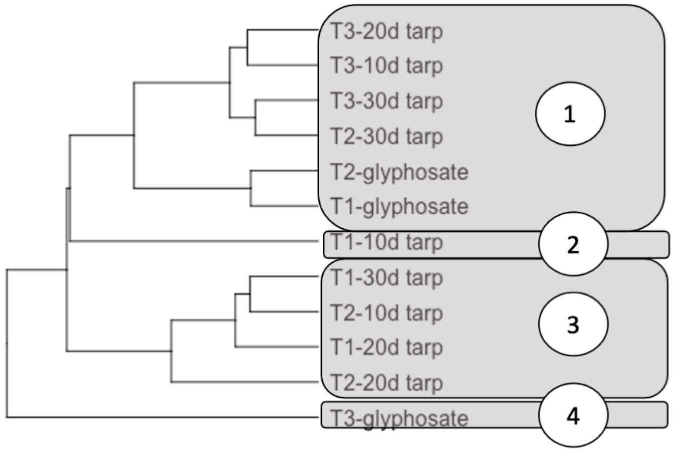

Figure 3.7: Dendrogram of weed communities at River Rise Farm, showing treatment groupings that had related weed communities.

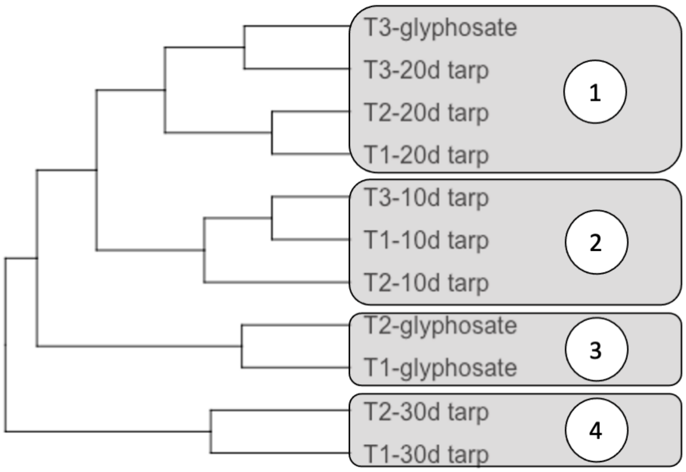

Figure 3.8: Dendrogram of weed communities at University of New Hampshire, showing treatment groupings that had related weed communities.. .

Only two groups from each site had significant indicator species (Tables 3.6 and 3.7). Many of the indicator species are ubiquitous in this region (Cordeau et al., 2017b, 2017a; Smith et al., 2018). In the context of filters, indicator species suggest that a group of treatments selects for that species, that other groups of treatments select against it, or both. At RRF, T1-10d (Group 2) had seven weed indicator species, and three of them were perennials. This supports the suggestion that short-duration occultation, especially in the absence of high levels of cover crop biomass, is ineffective at terminating all perennial weeds. The strength of the association, or the indicator value, was variable, however, with quackgrass (*Elymus repens* (L.) Gould) more strongly associated with T1-10d than yellow nutsedge (*Cyperus esculentus* L.). In other words, yellow nutsedge appeared in other treatments more frequently than quackgrass. This shows that the cover crop and occultation system can effectively suppress quackgrass provided sufficient cover crop biomass and duration of occultation, but yellow nutsedge escapes these filters. In mechanically terminated cover crop mulch, yellow nutsedge was unaffected by cover crop biomass or termination time (Mirsky et al., 2011).

Table 3.6: Indicator species at RRF of groups based on hierarchical cluster analysis of weed communities. Life history: SA=summer annual; P=perennial; WA=winter annual
Indicator value (IV) (0-1) represents the strength of the association between that species and the group.

Species	BAYER code	Common name	Group †	Life history	Grass/ forb	Periodicity/ emergence	IV	P value
Chenopodium album L.	CHEAL	Common lambsquarters	2	SA	Forb	Spring/early summer	0.96	0.001
Elymus repens (L.) Gould	AGRRE	Quackgrass	2	P	Grass		0.85	0.002
Amaranthus retroflexus L.	AMARE	Redroot pigweed	2	SA	Forb	Mid-spring-summer	0.67	0.002
Sinapis arvensis L.	SINAR	Wild mustard	2	WA/SA	Forb	Late summer, fall, spring	0.59	0.012
Cyperus esculentus L.	CYPES	Yellow nutsedge	2	P	Grass		0.48	0.034
Dactylis glomerata L.	DACGL	Orchardgrass	2	P	Grass		0.40	0.014
Capsella bursa-pastoris (L.) Medik.	CAPBU	Shepherd's purse	2	WA	Forb	Late summer, autumn, early spring	0.39	0.018
Taraxacum officinale F. H. Wigg.	TAROF	Dandelion	3	P	Forb		0.57	0.017

†Group 2= T1-10d occultation;

†Group 3= T1-30d occultation; T2-10d occultation; T1-20d occultation; T2-20d occultation

Other indicator species for T1-10d had various life history traits and emergence patterns (Myers et al., 2004; Uva et al., 1997). Unlike yellow nutsedge, small-seeded annuals are often strongly affected by cover crop biomass and termination time in mechanically-terminated cover crop mulch-based systems (Mirsky et al., 2011). Redroot pigweed (*Amaranthus retroflexus L.*) and common lambsquarters (*Chenopodium album L.*), which had relatively high indicator values for T1-10d, are two of the most common weeds present in the seedbank in northern New England. The fact that all treatments except T1-10d were effective at filtering them out suggests that the cover crop and occultation system holds promise for managing these common weeds.

Group 3, which was the only other group from RRF with an indicator species, had only one: dandelion (*Taraxacum officinale* F. H. Wigg). Dandelion was also the only species that was an indicator species at both sites. Although dandelion can be highly competitive with crops, it is also known to have the agroecosystem benefit of supporting arbuscular mycorrhizal fungi (AMF) (Kabir and Koide, 2000), unlike all of the annual species that were indicator species of T1-10d (Vatovec et al., 2005). Glyphosate and tillage, the two dominant weed management strategies in most annual cropping systems, both have been shown to lower AMF abundance (Druille et al., 2013; Jansa et al., 2002).

The effects of occultation on AMF abundance has not been studied, but it has been shown that solarization—the practice of using clear tarps that heat the soil more than black tarps—does not affect the infectivity of AMF (Schreiner et al., 2001). Solarization does, however, reduce AMF populations indirectly through a reduction of weed hosts, if a host crop is not planted. Managing weed communities as a way of managing AMF has been suggested as an integrated weed management strategy with multiple agroecosystem benefits (Jordan et al., 2000; Li et al., 2

Lee, New Hampshire016). Including mycorrhizal host plants in the field during the production of non-mycorrhizal crops like cabbage (*Brassica oleracea* var. capitata) maintains indigenous AMF populations and increases subsequent mycorrhizal crop yields (Karasawa and Takebe, 2012). Viewing weeds and weed traits for their agroecosystem benefits is a paradigm shift in weed management, and highlights the need for greater understanding of filters and weed community assembly (MacLaren et al., 2020). That is, shifting the goal from eradicating weeds toward coexisting with them requires that we understand the mechanisms that shape weed communities and populations and how these weeds in turn affect all aspects of the agroecosystem.

At UNH, dandelion, along with two other perennials, two winter annuals, and one summer annual were indicator species of Group 2, the 10d treatments. Like T1-10d at RRF, it appears that ten days of occultation was insufficient to terminate some perennial weeds. Indicator species from Group 4, which were all summer annuals suggest that 30d selected for later emergence, which could be a response to higher cumulative thermal units under tarps as well as effects of lower mulch. In a nearby field at UNH, large crabgrass (*Digitaria sanguinalis L.*) was an indicator species of early tillage events, showing that timing is a strong determinant of emergence (Cordeau et al., 2017a). It has been shown that an overwintering rye increases the persistence of large crabgrass seeds through decreased light exposure and reductions in fatal germination (Frost et al., 2019). It is possible that occultation, which continues to exclude light past cover crop termination, serves to protect large crabgrass seeds. Upon tarp removal, these seeds can germinate where there are gaps in mulch, and germination may be enhanced by higher nitrate levels under tarps (Rylander et al., 2020b). Crabgrass species (*Digitaria* spp.) are among the top two most problematic weeds reported by organic farmers, indicating that currently used management practices do not adequately filter the traits of crabgrass (Jabbour et al., 2014). These results show that the cover crop and occultation system has variable effects on these important weed species depending on implementation.

Table 3.7: Indicator species at UNH of groups based on hierarchical cluster analysis of weed communities. Life history: SA=summer annual; P=perennial; WA=winter annual
Indicator value (IV) (0-1) represents the strength of the association between that species and the group.

Species	**BAYER code**	**Common name**	**Group**†	**Life history**	**Grass/ forb**	**Periodicity/ emergence**	**IV**	**P value**
Stellaria media (L.) Vill.	STEME	Common chickweed	2	WA	Forb	Throughout summer	0.68	0.001
Erigeron annuus (L.) Pers.	ERIAN	Eastern daisy fleabane	2	SA	Forb		0.61	0.003
Trifolium repens L.	TRFRE	White clover	2	P	Forb		0.54	0.004
Taraxacum officinale F. H. Wigg.	TAROF	Dandelion	2	P	Forb		0.50	0.030
Cerastium fontanum Baumg. ssp. Vulgare	CERVU	Mouseear chickweed	2	P	Forb		0.43	0.003
Veronica arvensis L.	VERAR	Common speedwell	2	WA	Forb	Late summer, fall, early spring	0.26	0.031
Portulaca oleracea L.	POROL	Purslane	4	SA	Forb		0.87	0.001
Digitaria sanguinalis	DIGIS	Large crabgrass	4	SA	Grass	Mid-spring-late summer	0.76	0.001
Mollugo verticillate L.	MOLVE	Carpetweed	4	SA	Forb	Generally later than other summer annuals	0.75	0.001

†Group 2=T3-10d occultation; T1-10d occultation; T2-10d occultation
†Group 4=T2-30d occultation; T1-30d occultation; (T3-30d occultation was not harvested).

Strong filtering effects of termination time (RRF) and termination method (UNH) indicate that the cover crop and occultation system—like other strong filters—should be used as part of an integrated weed management strategy so as not to inadvertently select for weed species capable of tolerating or avoiding these management practices. There is flexibility in the cover crop and occultation system because cover crops can be terminated at any time and tarps can be left in the field for variable durations. Mulch appears to be the dominant variable responsible for affecting both weed biomass and weed communities in this system, although time likely played a role by selecting for weeds with different periodicities. This study allowed weeds to grow to their full potential, but it should be noted that a crop itself, as well as its spatial arrangement, can act as an additional filter on weed biomass and community assembly (Olsen et al., 2012; Smith and Mortensen, 2017; Wallace et al., 2018). Assessing weed community assembly in a single year at any site provides meaningful, but limited information about the long-term implications of management practices. Longer duration systems experiments are necessary to determine the best strategies to select for diverse, beneficial weed communities that have limited effects on yields and provide agroecosystem benefits (Smith et al., 2010).

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IV. CHAPTER 4: TRADEOFFS OF RYE-VETCH COVER CROP TERMINATION TIME AND METHOD FOR COVER CROP MULCH-BASED SYSTEMS

Abstract

Cover crop termination timing and method affect the tradeoffs between ecosystem services—which are primarily regulated by cover crop biomass quantity and quality—crop planting date, and environmental externalities. Leaving cover crop residue on the surface as an *in situ* mulch for no-till production eliminates the detrimental effects of tillage prior to crop planting, but requires effective cover crop termination strategies and sometimes necessitates additional weed management. Using a winter rye (*Secale cereale L.*)- hairy vetch (*Vicia villosa* Roth) cover crop, we investigated the effects of three termination strategies: herbicides, occultation with reusable tarps for ten, twenty, and thirty days, and roller-crimping, at three termination times on multiple ecosystem services. Using a tradeoffs framework, we explore the potential for cover crop mulch-based no-till systems.

Introduction

Overwintering cover crops are one of the most promising management strategies to balance environmental and production goals of agriculture in a changing climate (Kaye and Quemada, 2017; McClelland et al., 2021). When terminated and left on the soil surface, they provide *in situ* mulch that can suppress weeds, facilitate no-till planting, and buffer against extreme precipitation and drought, both of which are predicted to increase with climate change (Teasdale and Mohler, 1993; Hayhoe et al., 2007; Cavigelli et al., 2013). Furthermore, leguminous cover crops are an essential part of recoupling nutrient cycles in agroecosystems through biological N fixation (Drinkwater et al., 1998; Drinkwater and Snapp, 2007).

Despite the potential to provide multiple ecosystem services, cover crops can also interfere with crop production by delaying planting dates, immobilizing nutrients, and preemptively or actively competing (if not completely terminated) with cash crops (Leavitt et al., 2011; Halde et al., 2017; Vincent-Caboud et al., 2017; Hefner et al., 2020b). Species selection, termination time, and termination method are critical factors influencing the tradeoffs of ecosystem services within cover crop mulch-based systems. Flexibility in termination time and method are constrained by the growing season and farming system (i.e., if synthetic inputs are permitted), however, and tradeoffs must be assessed within this context.

A substantial body of research has shown that grass-legume bicultures like winter rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) can balance sometimes competing ecosystem services in cover crop mulch-based systems (Clark et al., 1994; Hayden et al., 2014; Poffenbarger et al., 2015b; Thapa et al., 2018). However, little research has been conducted in climates where short growing seasons and cold winters limit biomass production (Toom et al., 2019). Hairy vetch is the most winter hardy annual legume, and has greater potential to meet crop N needs because it contributes more biologically fixed N—sometimes exceeding 150 kg ha^{-1}— than other legume species with a lower C:N ratio (Hefner et al., 2020b; Perrone et al., 2020; Maher et al., 2021). However, growth and biomass accumulation of winter rye and hairy vetch can be asynchronous, with rye often reaching peak biomass and maturing earlier than hairy vetch (Wagger, 1989; Clark et al., 1994; Parr et al., 2011). Understanding how biomass quantity and quality (e.g., C:N ratio) changes with time in rye-vetch mixtures is important because ecosystem services are driven by both species (Finney et al., 2016; White et al., 2017). Most research has relied on a single cover crop termination date, with very little data illuminating the effects of termination time on biomass quantity and quality in rye-vetch mixtures (Clark et al., 1994; Parr et al., 2011; Lawson et al., 2015).

Asynchronous maturity also affects the efficacy of non-chemical termination methods, like roll-crimping, which relies on cover crop phenology (Mirsky et al., 2009; Mischler et al., 2010; Leavitt et al., 2011). Inadequate cover crop termination, combined with insufficient weed suppression and nutrient availability, have limited adoption of organic cover crop mulch-based no-till systems in northern climates (Halde et al., 2017). Reusable tarps, which are applied for a variable period of time and then removed prior to cash crop planting, are becoming common among small-scale organic vegetable farmers to control weeds (Fortier and Bilodeau, 2014).

In a recent survey of horticultural producers in the United States using cover crops, 4.7% said they used tarps to terminate cover crops while 3.8% used a roller-crimper and 23% used herbicides (CTIC, 2020). Preliminary evidence suggests the use of opaque tarps, sometimes called “occultation,” may make cover crop mulch-based systems viable for organic farmers (Lounsbury et al., 2020; Rylander et al., 2020a), but relationships between tarp application time, duration of tarping, and the resulting ecosystem services have not been studied. Because tarps require human power to apply and remove, they are currently limited to small-scale producers. In the absence of effective mechanical means to terminate cover crops, herbicides are the only viable method for larger producers to use cover crop mulch-based systems.

In this paper, we quantify the effects of termination time and method on ecosystem services and tradeoffs associated with a rye-vetch cover crop managed for *in situ* mulch to facilitate no-till planting. Termination methods included glyphosate or occultation with a reusable plastic tarp for durations of 10, 20, and 30 days, or roller-crimping alone. Our objectives were to i.) determine the effects of termination time on cover crop quantity (biomass and N) and quality (C:N ratio); ii.) determine the combined effects of time and termination method on the critical and sometimes competing ecosystem services of weed suppression and N provisioning; iii.) elucidate potential mechanisms behind observed ecosystem services by quantifying litter decomposition and microbial biomass; and iv.) characterize the tradeoffs of termination time and method on ecosystem services within cropping systems.

Materials & Methods

Field sites and experimental design

We conducted field experiments in 2017-2018 at River Rise Farm (RRF) in Turner, Maine (44° 19′ 27″N, 70° 11′ 22″ W) and in 2018-2019 at the University of New Hampshire's Woodman Horticultural Farm (UNH) (43° 09′ 05″ N, 70° 56′ 42″ W). These sites are in USDA hardiness zones 5a and 5b respectively. The soil at RRF is classified as Merrimac fine sandy loam (Sandy, mixed, mesic Typic Dystrudept) and has a surface soil (0–15 cm) pH of 6.6 and an organic matter content of 4.9%. The soil at UNH is classified as Charlton fine sandy loam (Coarse-loamy, mixed, superactive, mesic Typic Dystrudept) and has a surface soil (0–15 cm) pH of 5.5 and an organic matter content of 3.5%. The field at RRF had been in mixed vegetables and cover crops for the preceding seasons and the field at UNH had been in winter rye and summer annual cover crops for the two years prior to initiation of the experiment.

We seeded all plots to a cereal rye (*Secale cereale* L.) and hairy vetch (*Vicia villosa* Roth) biculture in late September. Prior to cover crop seeding, the RRF field was rototilled in early September and again immediately before seeding on September 25. At RRF, 'Wheeler' rye (Moore Seed Farm, Elsie, MI) and hairy vetch (VNS, Johnny's Selected Seeds, Winslow, ME) were seeded using a Brillion drop seeder at a rate of 115 kg ha^{-1} rye and 33 kg ha^{-1} vetch. The

UNH field was moldboard plowed on September 6 and harrowed on September 19, then seeded with 112 kg ha^{-1} rye and 34 kg ha^{-1} vetch (both VNS, Johnny's Selected Seeds, Winslow, ME) using a Kraus no-till drill on September 20, 2018, followed by a pass with a Brillion. Hairy vetch seed was inoculated with *Rhizobium leguminosarum* biovar. *viceae* (Verdesian LifeSciences, Cary, NC) at both sites prior to seeding.

The experiment was arranged as a split plot within a randomized complete block design with five replications at each site. The main plot treatments were three cover crop termination dates (T1, T2, and T3), approximately ten days apart in late spring (Table 4.1) and the sub-plot treatments were termination methods. Cover crops were rolled prior to the following termination methods: glyphosate, 10-day tarp application (10d), 20-day tarp application (20d), 30-day tarp application, and roller-crimp only (RC, at UNH only). The main plots were (3 x 12m) and (3 x 15m) at RRF and UNH respectively, with four and five 3 x 3m sub-plots, respectively. This design resulted in 12 and 15 treatment combinations at RRF and UNH respectively, with five possible "planting dates" for a subsequent crop (Table 4.1). It should be noted that the practice of "planting green" into cover crops at the time of, or even before, termination is possible, but many farmers delay planting after cover crop termination (Reed et al., 2019; CTIC, 2020). The "planting dates" presented here are hypothetical and represent 10 days after glyphosate application or roller-crimping, or immediately after tarp removal. No crop was grown in our experiment in order to assess the ecosystem services without the potentially confounding effects of a growing crop.

TABLE 4.1 Cover crop termination dates and resulting "planting dates" for each treatment in 2018 (RRF) and 2019 (UNH).

Termination time	Termination method	Termination date	Termination time GDD		'Planting date'†	'Planting date' GDD		'critical period' sampling date	'critical period' GDD	
			Base 4°	Base 10°		Base 4°	Base 10°		Base 4°	Base 10°
					RRF					
T1	10d tarp	13 June	607	293	23 June	758	385	16 July	1144	634
	20d tarp	13 June	607	293	3 July	919	486	25 July	1293	728
	30d tarp	13 June	607	293	13 July	1098	606	5 August	1498	868
	glyphosate	14 June	626	306	23 June	758	385	16 July	1144	634
T2	10d tarp	22 June	745	378	2 July	899	473	25 July	1293	728
	20d tarp	22 June	745	378	12 July	1082	596	5 August	1498	868
	30d tarp	22 June	745	378	22 July	1241	695	14 August	1664	980
	glyphosate	22 June	745	378	2 July	899	473	25 July	1293	728
T3	10d tarp	3 July	919	486	13 July	1098	606	5 August	1498	868
	20d tarp	3 July	919	486	23 July	1254	702	14 August	1664	980
	30d tarp	3 July	919	486	2 August	1442	829	23 August	1803	1065
	glyphosate	3 July	919	486	13 July	1098	606	5 August	1498	868
					UNH					
T1	10d tarp	22 May	378	149	1 June	479	201	26 June	807	386
	20d tarp	22 May	378	149	12 June	613	613	5 July	967	492
	30d tarp	22 May	378	149	21 June	730	339	17 July	1186	639
	glyphosate	23 May	389	155	1 June	479	201	26 June	807	386
	Roll-crimp only	22 May	378	149	1 June	479	201	26 June	807	386
T2	10d tarp	1 June	479	201	12 June	613	613	5 July	967	492
	20d tarp	1 June	479	201	21 June	730	339	17 July	1186	639
	30d tarp	1 June	479	201	1 July	892	441	26 July	1344	743
	glyphosate	3 June	499	210	NA	NA	NA	5 July	967	492
	Roll-crimp only	1 June	479	201	12 June	613	613	5 July	967	492
T3	10d tarp	12 June	613	274	21 June	730	339	17 July	1186	639
	20d tarp	12 June	613	274	1 July	892	441	26 July	1344	743
	30d tarp	12 June	613	274	12 July	1093	576	*NA		
	glyphosate	12 June	613	274	21 June	730	339	17 July	1186	639
	Roll-crimp only	12 June	613	274	21 June	730	339	17 July	1186	639

†Planting date is the date of soil sampling for inorganic N, and the date from which the "critical weed free period" was calculated.

*not harvested

Weather

Weather data were downloaded from weather station USC00178817 (Turner, Maine) for RRF and USW00054794 (Madbury, New Hampshire). Growing degree days were calculated using the following equation:

$$GDD = \frac{T_{\max} + T_{min}}{2} - T_{base}$$

Where T_{max} is the maximum daily temperature, T_{min} is the minimum daily temperature and mean tempertures below T_{base} are considered zero. We made calculations for different periods of the cropping sequence for T_{base} 4°C and 10°C to provide two quantitative ways to assess the tradeoff of delayed cover crop termination and tarp duration. These two base temperatures broadly represent different requirements for cool and warm season crops.

Cover crop termination

We rolled cover crops prior to tarp or herbicide application. At RRF, this was done with a 1.2 m water filled lawn roller (Brinly-Hardy) pulled by a riding lawnmower and at UNH with a 3 m rear-mounted roller-crimper (I & J Manufacturing, Gordonsville, PA). Glyphosate plots were sprayed within 3 days of rolling (Table 4.1). The formulations differed in the two years. Glyphosate used in 2018 was isopropylamine salt (50.2%) (Roundup Weed and Grass Killer, Monsanto) at the maximum label rate to ensure cover crop termination equal to 11.3 kg ha^{-1} acid equivalent. Glyphosate used in 2019 was isopropylamine salt (40.1%) at a 2% solution label rate equal to 12.2 kg ha^{-1} acid equivalent (Makaze, Loveland Products, Greeley, CO). For the tarp treatments, we used new 6 mil (0.15mm) black on white "silage" (low density polyethylene) tarps with the black side up. Tarps were secured using 15 cm sod staples placed approximately every meter along the edges.

Cover crop quantity and quality at termination

To assess cover crop biomass and C:N, we harvested one 0.25m^2 quadrat from each sub-plot plot prior to each termination date on June 10, June 21, and July 1 at RRF and May 21, May 31, and June 10 at UNH. All stems originating within the quadrat were clipped at the ground level. Rye, vetch, and weeds were separated and dried at 65° C. A subsample of rye and vetch from each plot was ground to pass a 0.841mm sieve with a Wiley Mill and then homogenized using a cell disrupter (Mini-Beadbeater96, BioSpec Products, Bartlesville, OK). These samples were analyzed for total carbon (C) and nitrogen (N) using a Primacs SNC-100-IC TOC/TN analyzer (Skalar, The Netherlands) or a Costech C/H/N/S Elemental Analyzer (Costech, Valencia, CA) (separated by block). The C:N ratio of the mixture was determined using the C and N concentrations and mass of each species to calculate a weighted average for the cover crop mixture.

Residue decomposition (Litter bags)

We deployed litter bags with fresh cover crop material at each termination date in each sub-plot in order to determine how termination methods affected mulch degradation over time. Litter bags remained in the field for 30 days at RRF and 30 and 60 days at UNH. To create the litter bags, we filled 0.20m x 0.20m bags of screen mesh (0.33mm opening) with fresh cover crop material. The cover crop material was harvested from an area of the field outside of the experimental plots before each cover crop termination date. We filled each litter bag with fresh biomass proportional to T1 quadrat samples from each year on a per area basis. In order to keep the volume of material in the litter bags relatively consistent throughout the termination dates and to keep within the size limitations of the litter bags, we kept this fresh weight constant for T2 and T3, despite changes in biomass quantity in the field.

To approximate the cover crop quality present in the field at each termination date and to ensure consistent composition between litter bags, each litter bag contained a ratio of rye to vetch that was equivalent to the average of that measured in the fresh biomass quadrats from that termination date. Additionally, we separated the cover crop material for the litter bags into individual plant components, the ratio of which was recorded and reproduced in each litter bag. Rye was separated into leaves, stems, and heads, and vetch was separated into leaves and stems on T1 and T2. On T3, rye stems and leaves were separated from rye heads and vetch was not separated. At RRF, we did this activity outdoors and it is likely that the cover crop material lost moisture during the process, resulting in higher biomass equivalents in the litter bags than existed in the field (Table 4.2). At UNH, we did this indoors and more quickly to prevent moisture loss, and this likely resulted in biomass contents more closely matching those in the field.

To maintain a constant volume of plant material within each litter bag at each termination time and site, we kept starting fresh weights constant. Relative moisture of cover crop tissue changed during the season and this compromise resulted in an increasing dry matter equivalent in the litter bags with later termination dates at each site (Table 4.1) equal to 1.1 Mg ha^{-1} from T1-T3 at RRF and 1.0 Mg ha^{-1} at UNH. Additionally, the C:N of the litter bag source material was slightly different from means within the experiment, which varied between blocks (Table 4.2; Figure 4.3).

We cut plant material into ~15 cm pieces before adding to the litter bags, which were sealed with staples. They were kept cool (7°C) for up to one day prior to application in the field. A subsample of the component plant parts was weighed at the time of litter bag assembly and was then processed and analyzed for moisture content and total C and N according to the same protocol as the biomass samples. These data were used to calculate the C and N content of each litter bag.

We put litter bags in the field after rolling, prior to tarp and herbicide application. They were placed directly on the soil surface in areas where biomass quadrats had been harvested and were held down with additional cover crop biomass around the edges, but not in the center of the bags that held litter. After removal, all litter bag material was dried at 65°C for >48 hours. Dry litter material was ground and prepared for C:N analysis following the same protocol as the biomass samples. The fraction remaining in litter bags of total material, C, and N was calculated as the final value subtracted from the initial value.

Table 4.2: Contents of litter bags deployed at RRF and UNH in 2018 and 2019 respectively

	RRF			UNH		
	T1	T2	T3	T1	T2	T3
				Rye head		
Fresh weight (g)	7.7	5.9	7.6	9.4	11	6.3
% moisture[†]	62	54	57	78	70	60
C:N	20	29	26	20	21	24
				Rye leaves		
Fresh weight	3.7	2.7		15	9.7	
% moisture	74	46		75	77	
C:N	20	56		19	22	
				Rye stems		
Fresh weight (g)	29	23	27	53	55	51
% moisture	70	55	52	82	77	70
C:N	49	64	56	53	62	74
				Vetch stems		
Fresh weight (g)	9.8	12		4.8	6.1	
% moisture	79	76		84	85	
C:N	19	18		15	20	
				Vetch leaves		
Fresh weight (g)	20	28	35	9.5	11	35
% moisture	77	79	79	83	84	86
C:N	8.5	8.5	13	7.8	9.0	11
Overall C:N	19	21	26	24	30	30
Total biomass equivalent (Mg ha^{-1})[‡]	4.9	5.7	6.0	4.6	5.2	5.6

[†] Cover crop material was separated outside at RRF and likely lost moisture during the process.

[‡] Because of moisture loss from the cover crop material used for litter bags, the biomass deployed in the field was substantially more than the estimated cover crop biomass that year.

Soil responses after termination

To assess the effects of the treatments on soil moisture and nitrogen dynamics, we took four soil samples (0–15cm) using a 2 cm soil probe from each sub-plot on the termination day and again on the 'planting date' (Table 4.1). Soil moisture content was determined by drying a sieved (<2mm) subsample at 65°C for 48 hours. Inorganic N from UNH was extracted from 10.0g fresh, sieved (<2mm) field moist soil using 50mL 2 M KCl solution, shaken for 30 minutes on an orbital shaker and filtered through #40 filter paper (Whatman). Concentrations of inorganic N were determined colorimetrically using a Lachat autoanalyzer (Latchat Instruments, Milwaukee, WI) employing a cadmium reduction/sulfanilamide method for NO_3-N and a hypochlorite/salicylate method for NH_4-N (Lachat QuikChem Method 10-107-04-1-F). Net mineralization was calculated as the total inorganic N concentration on the post-treatment sample date minus the initial concentration on the cover crop termination day.

Soil microbial biomass

Additional soil samples were taken at the completion of the experiment at UNH, on August 6, 2019, in order to determine how the treatments influenced soil microbial biomass. Soil microbial biomass was quantified using a modified chloroform fumigation extraction (Vance et al., 1987) using a 0.05 M K_2SO_4 extraction on field moist, sieved (<2mm) samples. Extracts were analyzed for total organic carbon via thermal oxidation with near infrared carbon detection (Shimadzu TOC-L). Values were not adjusted for extraction efficiency, as extraction efficiency was unknown (Haney et al., 2001).

Weed biomass and mulch remaining after the critical weed-free period

We harvested cover crop mulch remaining on the soil surface and weeds 22-25 days after ‘planting date.’ This timing was intended to approximate the critical weed-free period for many crops, although this is highly context-dependent (Knezevic et al., 2002). We harvested weeds from two 0.25 m^{-2} quadrats per plot by cutting them at the soil surface. Cover crop regrowth occurred in some treatments, which was harvested. We then cut the residue around the interior edge of each quadrat using a knife, then cut remaining stems at the soil surface. Both weeds and mulch were dried at 65°C for >48 hours and then weighed. Some soil contamination of mulch was visible and inevitable, but this method is a coarse estimate of mulch remaining in the field. We harvested weeds in the same manner at the conclusion of the experiment (i.e. the same time for all treatments), and regressed these data with microbial biomass carbon.

Analyses

All analyses were performed within the R environment (R Core Team, 2020). Cover crop biomass, N content, and C:N ratio were analyzed using linear mixed models with block as a random factor and site and termination time as fixed factors. If there was a significant site interaction, analyses were performed for individual sites. Litter bag, weed biomass, and soil data were analyzed with termination time and termination method as fixed factors. Block was a random factor nested within site. Because RC was present at UNH and not RRF, models were first run without RC to look for main effects. When sites were analyzed individually, RC was included at UNH. All analyses were performed using “lme4” package in R (Bates et al., 2015) with Type III sums of squares, and means comparisons were assessed using Tukey’s multiple comparison test with the “emmeans” package in R (Lenth, 2020). Data that violated only the normality assumption of ANOVA were not transformed (Schmider et al., 2010). All figures were created with the 'ggplot2' package (Wickham, 2016).

For visualization of tradeoffs in ecosystem services between treatments we used spider plots (Schipanski et al., 2014; Snapp et al., 2015). Spider plot axes were scaled according to the data at each site. For cover crop biomass, cover crop N, mulch, and soil N, values were relativized with the mean value of the treatment divided by the highest mean value among all the treatment at that site. In other words, each axis is scaled from zero to the highest performing treatment combination at that site. For a weed suppression value, the mean weed biomass of each treatment was divided by the highest mean weed biomass for the site, and then this number was subtracted from 1. At UNH, where there was incomplete cover crop termination for some treatments, cover crop regrowth was included in weed biomass to calculate the weed suppression value.

Results

Weather and effects of termination time on cumulative GDD

Temperatures and GDD at RRF were similar to the 15-year average in spring, but precipitation was much lower than average during periods of cover crop growth in May and June as well as the subsequent months of cover crop decomposition and weed growth (Tables 4.3 and 4.4). At UNH, temperatures and GDD were below average. Precipitation was highly variable in the months of March through July, but on the whole was closer to average than RRF. Termination times occurred at UNH earlier in the calendar year and with lower GDD than RRF. The ten-day spacings from T1–T2 and T2–T3 at RRF had more thermal units (164 and 146 GDD) than at UNH (101 and 118 GDD).

Table 4.3 Monthly average temperature and precipitation and deviation from historical (2002-2017) norm in Turner, Maine (2017-2018) and Durham, NH (2018-2019) for RRF and UNH respectively.

		Sep	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**
							—°C—						
RRF	Average temperature	13.6	9.6	-0.6	-8.7	-9.1	-4.6	-3.1	0.8	9.6	13.5	17.7	17.7
	Deviation from norm	1.4	3.4	-1.4	-3.5	-0.5	3.6	0.6	-2.2	0.5	-0.4	0.5	1.7
							—mm—						
	Precipitation	139	182	48	95	152	81	84	128	35	79	94	63
	Deviation from norm	40	30	-64	-24	80	-4	-2	9	-76	-57	-10	-45
							—°C—						
UNH	Average temperature	17.4	8.4	1.6	-1.1	-4.8	-3.1	0.1	7.5	11.9	17.5	22.6	20.6
	Deviation from norm	1.0	-1.5	-2.7	0.3	0.0	0.3	-0.9	0.2	-1.2	-0.2	1.4	0.3
							—mm—						
	Precipitation	142	114	259	83	112	83	47	138	76	131	114	89
	Deviation from norm	42	-22	157	-33	38	-17	-62	28	-28	17	6	-9

Table 4.4 Cover crop growing degree days (GDD; base 4°C) in fall and spring in Turner, Maine (RRF) and Durham, NH (UNH) during the experiment years and the historical average. Numbers differ from Table 4.1 because of up to three day period between biomass sampling and cover crop termination.

		RRF		UNH	
		2017-2018	15 year average ‡	2018-2019	15 year average
Fall †		247	190	299	391
Spring					
	T1	568	562	368	410
	T2	732	705	469	521
	T3	878	874	587	641
Total					
	T1	815	752	667	801
	T2	979	895	768	912
	T3	1125	1064	886	1032

†Calculated on fall emergence date of 10/10 for RRF and 9/25 for UNH

‡Historical: average 2002 until experimental year

Efficacy of termination methods and cover crop maturity

All treatments at RRF were 100% effective at terminating cover crops. At UNH, neither RC nor 10d were effective at terminating rye on T1, but they were effective at T2 and T3 (Figure

4.1). Vetch regrowth following RC was greater than vetch biomass measured at all three termination times (Figure 4.2). While there was a small amount of vetch regrowth with the 10d treatment at T1, all other tarp treatments were close to 100% effective at terminating vetch. In plots where cover crops regrew after tarping, the plants were visibly not dead when tarps were removed. At RRF, rye was at >50% anthesis at T1 and nearly 100% anthesis by T3, while vetch was still vegetative at T1, at early flowering at T2, and >50% flowering at T3. At UNH, rye was <50% anthesis at T1, >50% anthesis at T2, and nearly 100% anthesis at T3, while vetch was vegetative at T1 and T2, and early flowering at T3.

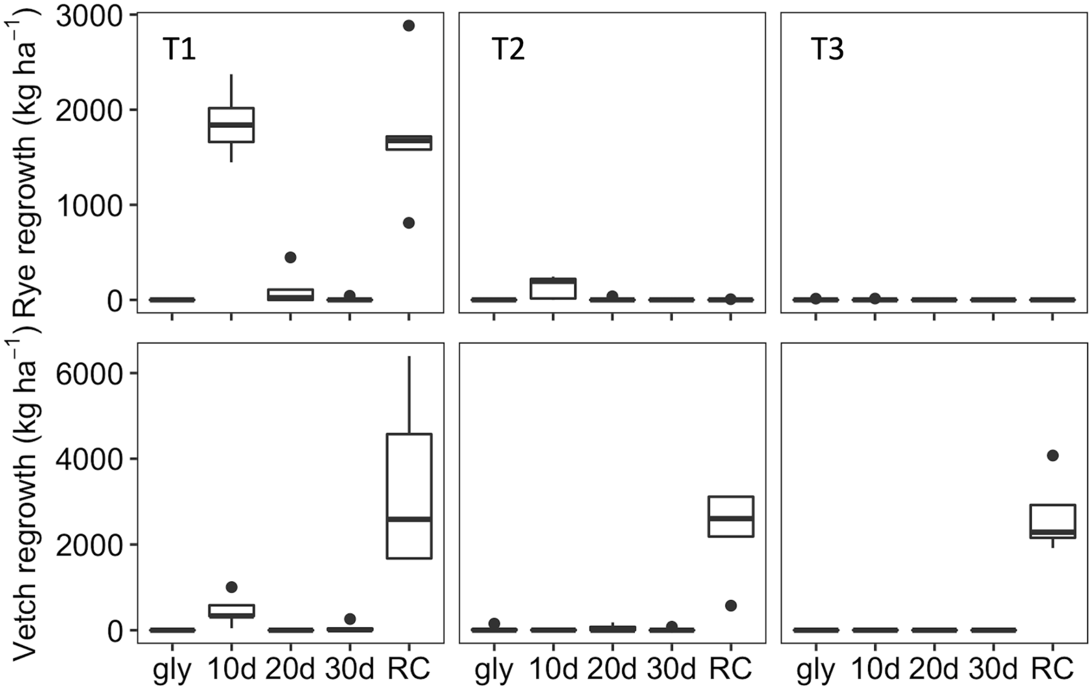

Figure 4.1: Cover crop regrowth measured after the “critical weed free period” for five termination methods (gly=glyphosate; 10d= 10 day tarp; 20d=20 day tarp; 30d= 30 day tarp; RC=roll-crimp) and three termination times (T1= May 22, T2= June 1, T3= June 12) in Durham, NH. Cover crops were grown in winter rye-hairy vetch biculture, but regrowth of individual species are presented. Note different axes.

Cover crop quantity

Total cover crop biomass increased significantly with each termination time at both sites. Although the patterns appear similar, there was a significant site*termination time interaction (p=0.018) and therefore the data from each site are presented separately (Figure 4.2). Changes in total biomass of the individual species also varied between sites and with termination time. Hairy vetch biomass was significantly higher at RRF than UNH (p=0.024), but growth with time followed the same pattern both sites. Hairy vetch biomass increased <50% between T1 and T2, but nearly doubled between T2 and T3. Winter rye followed different growth patterns at the two sites; biomass increased 35% during the whole period at RRF, while it increased 42% between T1 and T2 and only 3.5% after that at UNH. The growth differential between winter rye and hairy vetch resulted in a change in rye/vetch ratio at RRF from 2.0 at T1 to 1.2 at T3 and from 7.4 to 2.7 at UNH.

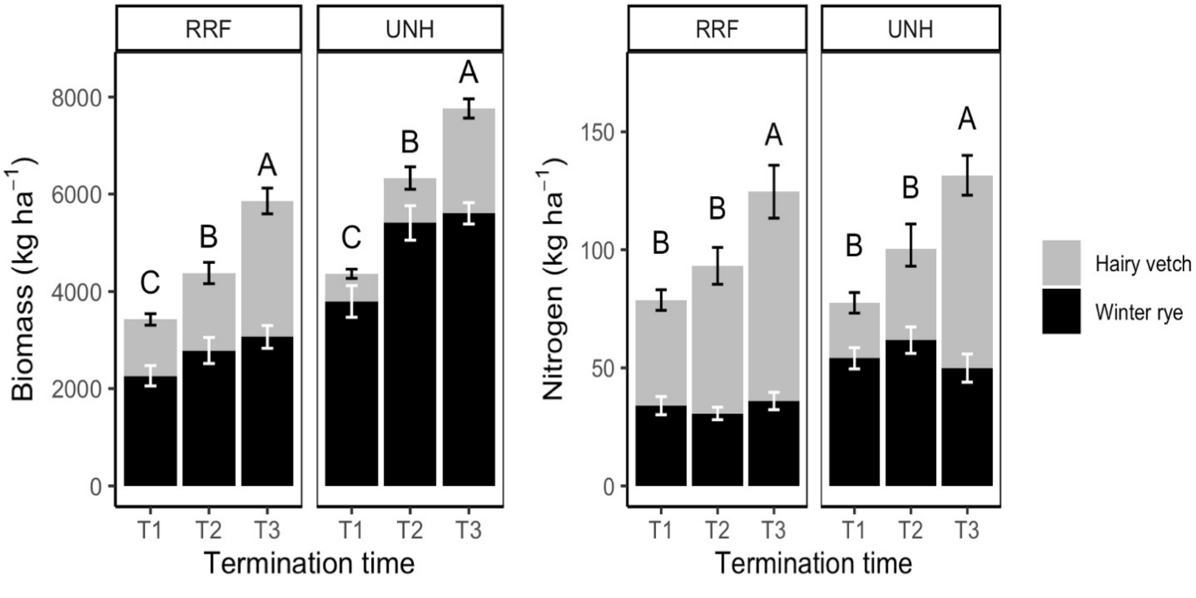

Figure 4.2: Winter rye and hairy vetch aboveground biomass and nitrogen content at three termination dates in Turner, ME (RRF) and Durham, NH (UNH). Cover crops were grown in biculture. Error bars represent +/-standard error of the mean (n=5) for each cover crop species and letters represent differences in the total cover crop biomass or nitrogen according to Tukey's multiple comparison test (α=0.05).

Total nitrogen content of the cover crop biomass was very similar between the two sites, with means at each termination time ranging from 79-125 kg ha^{-1} N at RRF to 78-132 kg ha^{-1} N at UNH over the 20 day period (Figure 4.2). A combined ANOVA model with both sites indicated that termination time was significant ($p=<0.0001$), and changes in total N did not occur until T3. This coincides with the increase in hairy vetch biomass (Figure 4.2). By T3, the proportion of N held in the hairy vetch biomass was 72% (89 kg ha^{-1}) at RRF and 62% (82 kg ha^{-1}) at UNH. Maximum N accumulation by winter rye had already occurred by T1 at both sites, as the total N content of winter rye did not change at any of the termination times ($p=0.62$). Total N in winter rye was higher at UNH (55 kg ha^{-1}) than at RRF (33 kg ha^{-1}).

Cover crop quality

C:N ratio of the combined cover crop material varied little between the termination times at each site, never exceeding 21 at RRF and 28 at UNH, despite increases in the winter rye C:N ratio (Figure 4.3). This is a function of the stable C:N ratio of hairy vetch, which remained between 10 and 13 at both sites throughout the period, combined with an increasing proportion of hairy vetch biomass (Figure 4.2). There was a significant site by termination time interaction ($p=0.0030$) for the winter rye C:N ratio, which reached a maximum of 39 at T2 at RRF, but increased until T3 at UNH, when it reached 51.

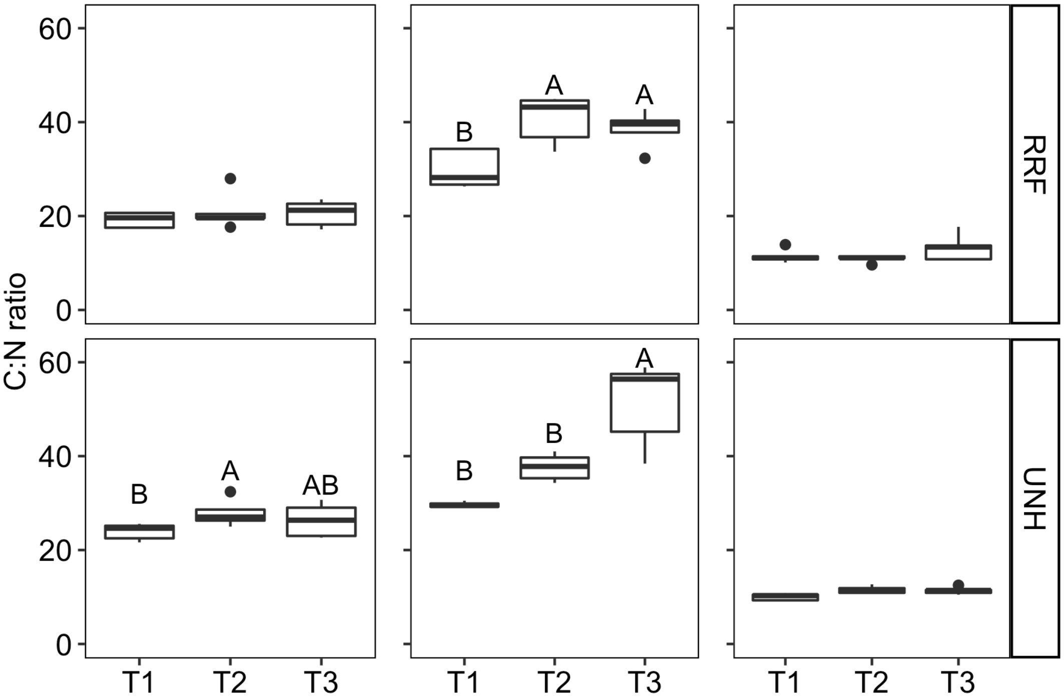

Figure 4.3: C:N ratio of winter rye-hairy vetch cover crop material at three termination times (T1, T2, T3) ten days apart in Turner, ME (RRF), and Durham, NH (UNH). Cover crop was grown as a biculture, but data are presented for combined cover crop material (left) as well as winter rye (middle) and hairy vetch (right) components. Means with the same letter are not different according to Tukey's multiple comparison test (α=0.05).

Residue decomposition (litter bags)

Termination time and method affected C and N loss from litter bags, with consistent patterns between sites despite differences in initial C:N ratios of litter bag contents (Figures 4.4-4.6). N loss from litter bags ranged from 35-51%, while C loss ranged from 21-46%. Delayed termination resulted in greater N retention, independent of termination method or site (Figure 4.5). C retention was higher than N retention, and C retention increased with delayed termination at UNH (Figure 4.6). At UNH, this pattern was clearer than at RRF, where differences between T2 and T3 were not evident and not detectable because of interactions between termination time and method (Figure 4.7). The effects of termination method on C and N losses mostly correlate with the time of exposure to the elements. Litter bags that were exposed to the elements for ≥ 20 of the 30 days they were in the field (i.e., glyphosate, 10d, and RC), retained less C and N than those that were under tarps for the majority of their deployment (i.e., 20d, 30d).

During the period of litter bag deployment, cumulative degree days (base 0°C, (Singh et al., 2020)), based on air temperatures were similar for all three termination times at RRF but increased at UNH (Table 4.5). However, air temperatures do not account for the moderating effects of mulch and tarps at the soil surface. Tarps lower the daily temperature fluctuation, with higher minimum temperatures at night, and lower or similar maximum temperatures during the day. This effect increases cumulative thermal units. This is discussed in greater detail in Chapter 3.

Table 4.5: Decomposition degree days after termination (base 0° C air temperature)

RRF		DDD	UNH	DDD
T1	30day	631	30day	507
T2	30day	633	30day	533
T3	30day	666	30day	616

Litter bags deployed for 60 days at UNH showed that main effects of both termination time (p<0.0001) and method (p=0.0001) on the amount of C remaining persisted beyond 30 days. Only 38% of C remained from T1, while 56% remained from T3. The only significant difference in termination methods was that less C remained in RC litter bags than all other treatments. Termination time, but not method, remained a significant driver of N remaining in litter bags after 60 days. Nearly 50% of N remained in litter bags from T3, in contrast to 45% from T2 (p=0034) and 42% from T1 (p<0.0001).

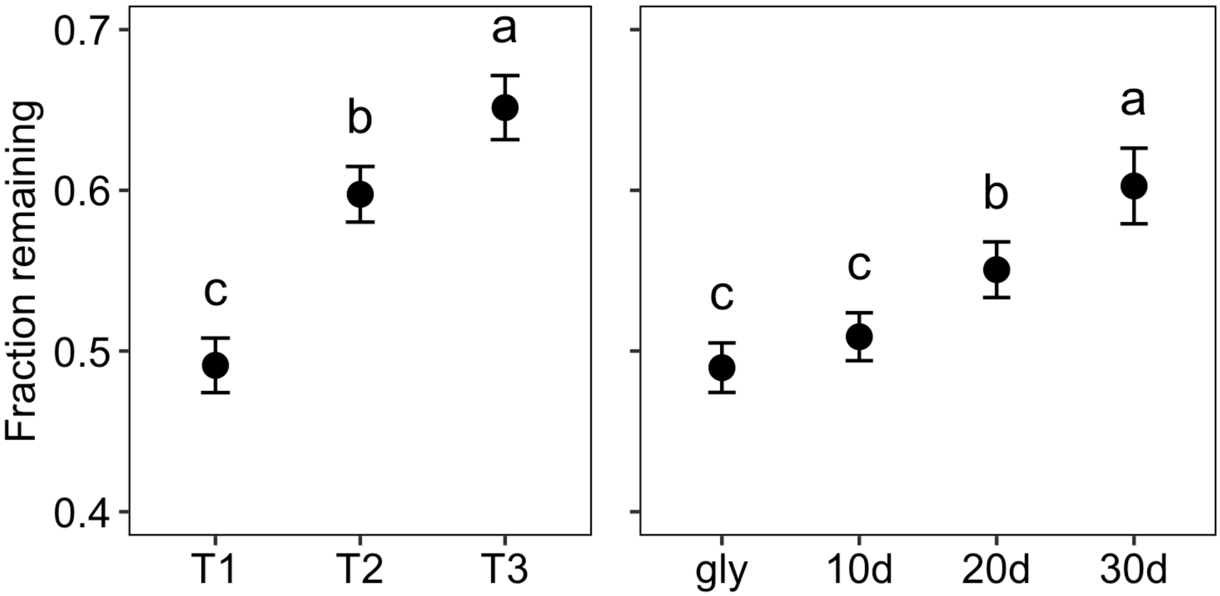

Figure 4.4: Fraction of N remaining in litter bags 30 days after termination time at two sites. Sites are pooled and means of termination time (left) and termination treatment (right) are presented (n=45 for termination time and n=30 for treatment). Bars are +/- standard error of the mean. Means with the same letter within each panel are not different according to Tukey's multiple comparison test (α=0.05).

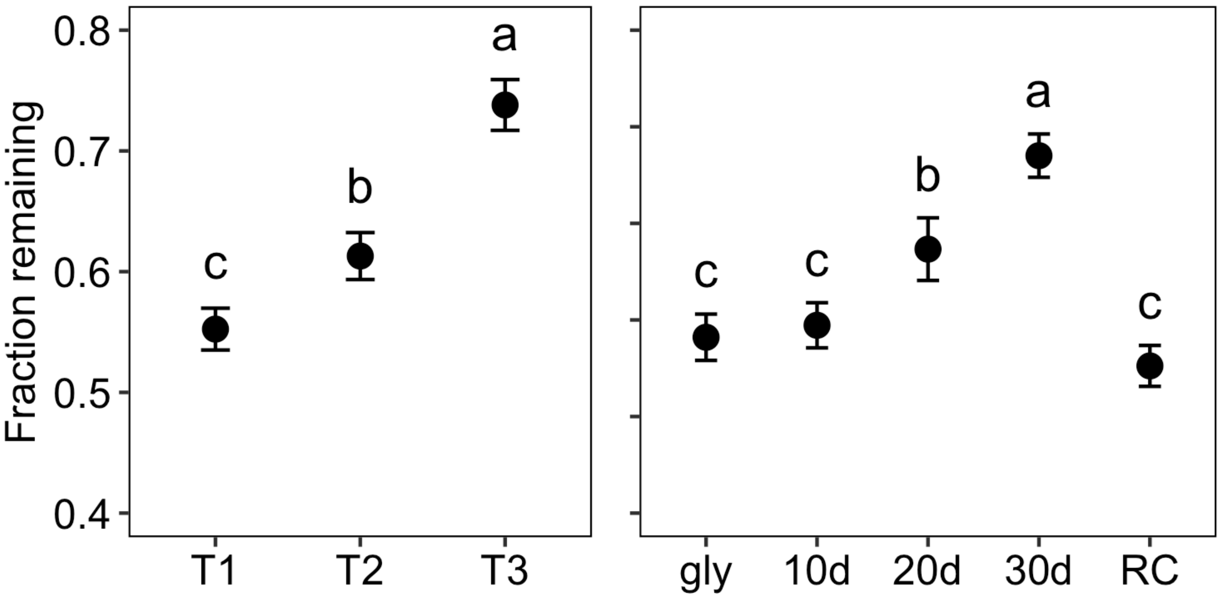

Figure 4.5: Fraction of C remaining in litter bags 30 days after termination time at UNH. Means of termination time (left) and termination treatment (right) are presented (n=25 for termination time and n=15 for treatment). Bars are +/- standard error of the mean. Means with the same letter within each panel are not different according to Tukey's multiple comparison test (α=0.05).

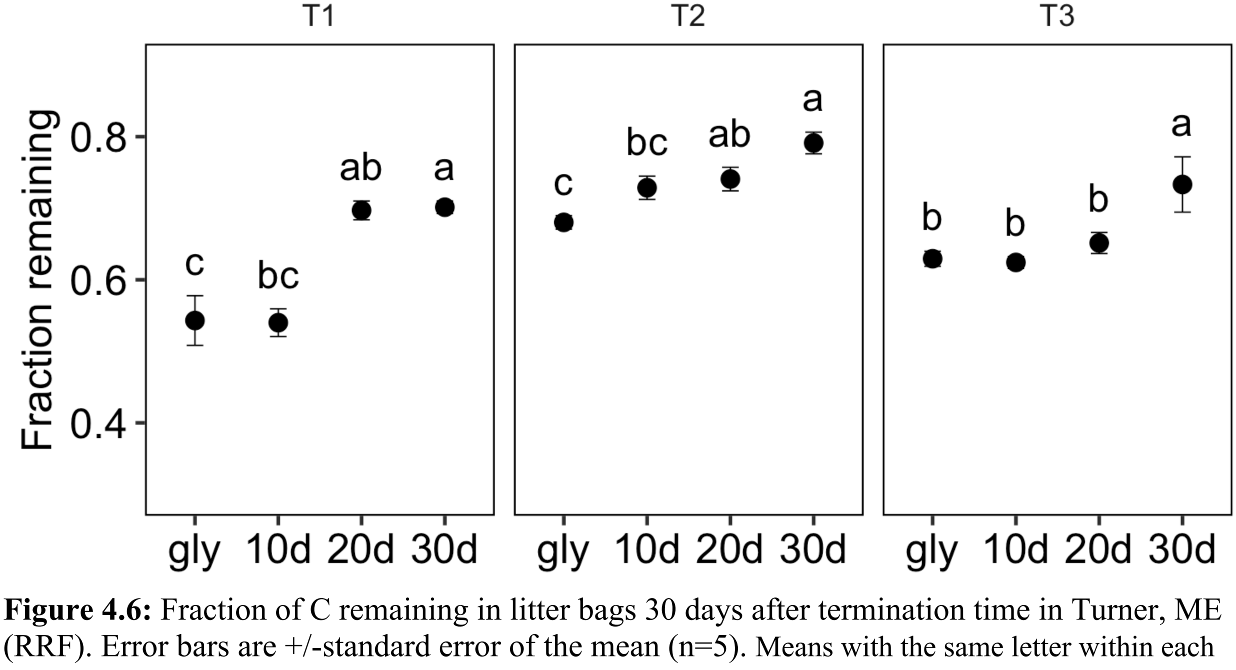

Figure 4.6: Fraction of C remaining in litter bags 30 days after termination time in Turner, ME (RRF). Error bars are +/-standard error of the mean (n=5). Means with the same letter within each termination time are not different according to Tukey's multiple comparison test (α=0.05).

Soil mineral N and moisture

Initial soil inorganic N concentrations at UNH were low at all termination times, ranging from 3.6 to 4.8 mg kg^{-1}. After termination during the 10 day period before the 'planting date,' low levels of net N mineralization (<6 mg kg^{-1}) occurred in 10d, glyphosate and RC across all termination times (Figure 4.7). Greater net mineralization occurred with longer tarp duration and later termination times, reaching a maximum of 33 mg kg^{-1} for T3-30d. However, there was a significant termination time by method interaction ($p<0.0001$), that is captured by the different magnitude of the effect of 30d from T1 to T3. NH_4^+-N concentrations never exceeded 4.4 mg kg^{-1} in the post-termination samples.

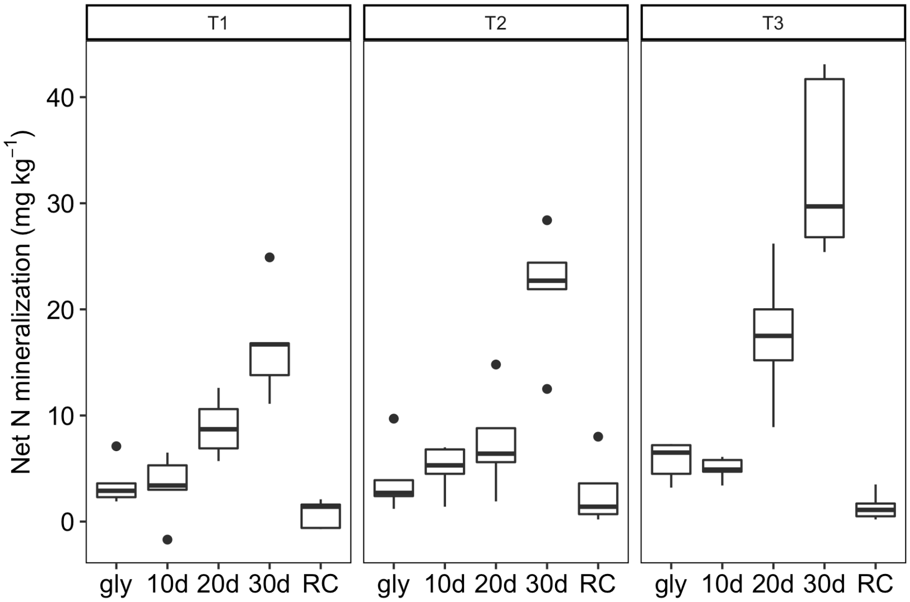

Figure 4.7: Net N mineralization at 'planting date' UNH following three cover crop termination times ten days apart (T1-T3) terminated with either glyphosate (gly), 10-day tarp (10d), 20-day tarp, 30-day tarp (30d) or roller crimping alone (RC).

Initial soil moisture differed slightly between termination times at UNH. The highest occurred at T3 with an average of 22% gravimetric moisture content, which was more than both T1 at 20% ($p=0.001$) and T2 at 19% ($p<0.0001$). The change in moisture content from termination time to ‘planting date’ was <1% gravimetric moisture content for all tarp treatments at UNH. At RRF, moisture content was 24-26% initially at all termination times. Soil moisture declined for all termination methods between termination time and “planting date,” however, to 19-20% gravimetric moisture content for T1 and T2. It remained at 26% for T3.

Microbial biomass

Microbial biomass carbon at the conclusion of the experiment was affected only by termination time ($p=0.029$) and not by termination method ($p=0.15$). The latest termination time (T3) had 33% lower MBC (-16 mg kg^{-1} dry soil) than T2 ($p=0.04$), and 30% lower MBC (-14.7 mg kg^{-1}) than T1($p=0.06$). To determine if this was a function of greater living biomass (i.e., weeds and cover crop regrowth) in T1 and T2, we regressed total living plant biomass with MBC and there was no correlation ($R^2=0.03$, $p=0.10$).

Weed biomass and mulch after the critical weed free period

Weed biomass and mulch dynamics are discussed in detail in Chapter 3, with the exception of the RC treatment at UNH. Generally, weed biomass after the critical weed free period was correlated with remaining mulch, but mulch levels were more related to termination time at RRF and termination method at UNH. At UNH, weed biomass in RC was not meaningful by itself, given the substantial cover crop regrowth. Cover crop regrowth also complicates interpretation of T1-10d, as the actively growing cover crop likely suppressed weeds. At both sites, glyphosate provided the most consistent weed suppression across termination times, but at T2 and T3 of both RRF and UNH, some or all of the tarp treatments were equally weed suppressive. In addition to weed biomass, termination time and method had effects on the weed communities, which are discussed in Chapter 3.

Effects on planting date & tradeoffs

The tradeoffs of ‘planting date,’ cover crop quantity (biomass, total N), N availability at the ‘planting date’ (UNH only), mulch, and weeds after the ‘critical weed free period’ at each site are summarized with spider plots in Figures 4.8-4.9. These spider plots present data that have already been presented in the text or Chapter 3, with some modification. Soil N is presented as inorganic N measured at planting date, rather than net mineralized N (Figure 4.7) and the weed suppressive value includes cover crop regrowth as well as weeds. In this way, weed suppressive value is a combination of termination efficacy and weed suppression. It should be noted that the axes for all values except weed suppression range from zero to the highest value observed, whereas weed suppression is scaled using only observed mean effects, i.e., the lowest weed suppression value is a function of the treatments included. At UNH, the scale of the weed suppression axis was strongly influenced by the cover crop regrowth in RC and T1-10d and had a much larger range than at RRF, where all treatments were highly weed suppressive in comparison.

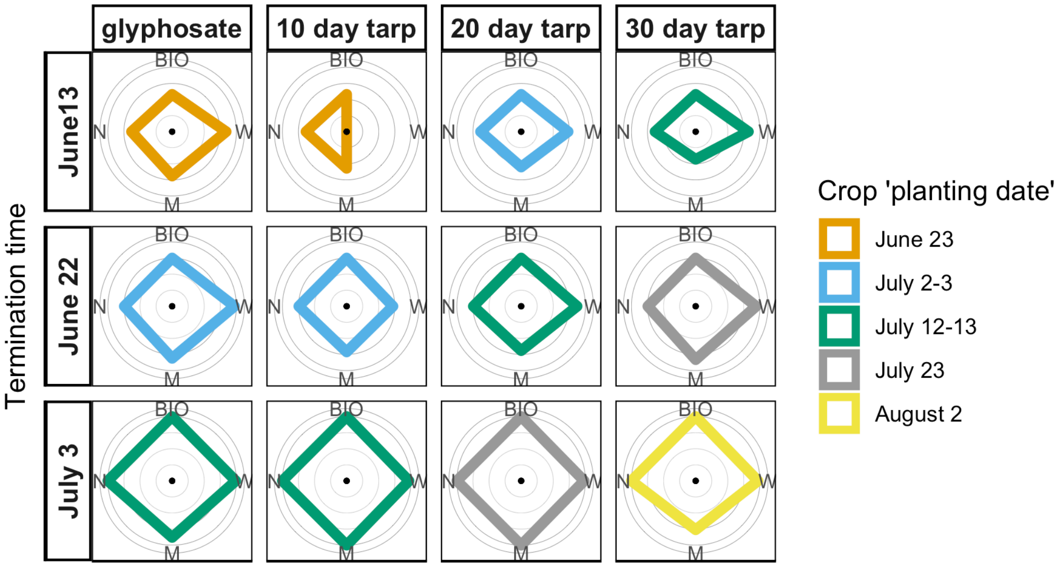

Figure 4.8: Spider plots showing ecosystem service tradeoffs with the different treatment combinations at River Rise Farm. (Abbreviations: W=weed suppression during critical period of weed control; M=mulch after critical period of weed control; N=N content of aboveground cover crop biomass; BIO=aboveground cover crop biomass).

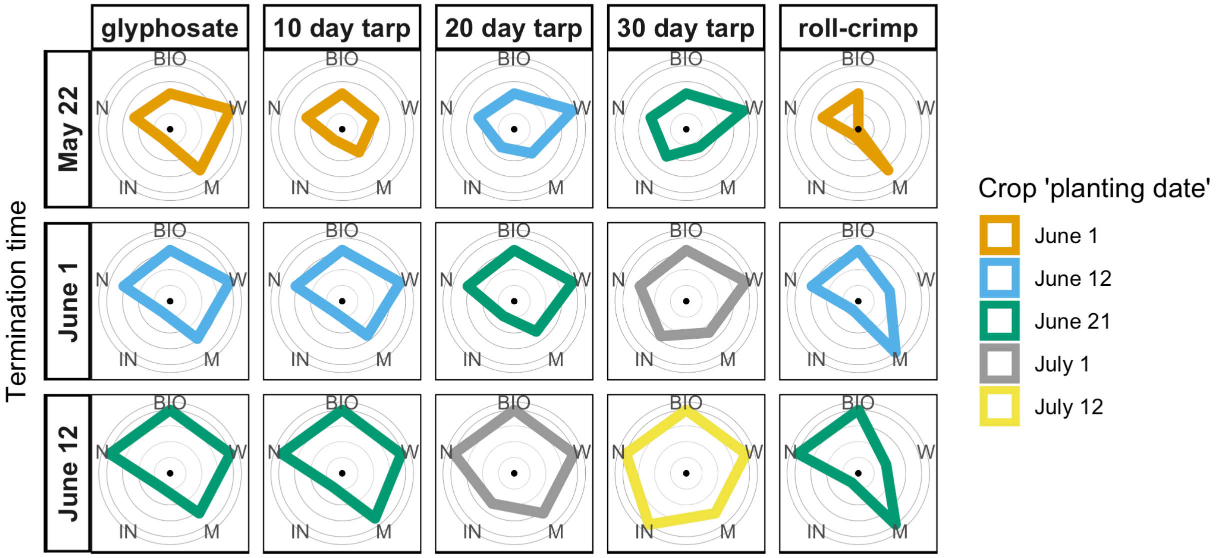

Figure 4.9: Spider plots showing ecosystem service tradeoffs with different treatments at University of New Hampshire. (Abbreviations: W=weed suppression during critical period of weed control; M=mulch after critical period of weed control; IN=inorganic N on “planting date”; N=N content of aboveground cover crop biomass; BIO=aboveground cover crop biomass)

Discussion

Cover crop termination

Incomplete termination of winter rye-hairy vetch cover crops with a roller-crimper is well-documented when termination is attempted before hairy vetch has reached early podset (Mischler et al., 2010; Leavitt et al., 2011; Boydston and Williams, 2017; Lounsbury et al., 2020). Hairy vetch regrowth at all three termination times at UNH in the roller-crimping only treatment is therefore not surprising and highlights the difficulty with mechanical termination of winter rye-hairy vetch cover crops in a short growing season. Inflexible timing is a severe limitation of systems that rely only on mechanical termination of cover crops (Halde et al., 2017; Vincent-Caboud et al., 2017; Lounsbury et al., 2020).

Unlike the body of literature on roller-crimping, there is no published evidence of the efficacy of tarps for terminating cover crops aside from our previous report (Lounsbury et al., 2020). The substantial regrowth of rye following the 10d treatment on T1 at UNH indicates that the resilience of rye to tarping is more dependent on rye maturity than thermal units, as the GDD for the ten day periods following T1 and T2 were similar (101 vs. 118). From a practical standpoint, a farmer would be able to tell that the cover crops under tarps were still alive simply by pulling up a corner and could determine if a longer duration of tarping is needed. It is notable that hairy vetch was susceptible to termination with tarps, even at the vegetative stage, but the minimal regrowth after 10d at UNH shows that under these weather conditions, a shorter tarp period would not have been sufficient. At other termination times, it is possible that an even shorter duration would have been adequate and more resolution on the relationship between cover crop maturity, weather, and the required tarp duration to terminate cover crops would aid management decisions.

Cover crop quantity

Our data show that hairy vetch growth and N accumulation accelerates after rye biomass and N capture have already peaked, even over a relatively short period of 10 or 20 days. This has important implications for crop N availability and weed suppression from cover crop residues. Numerous studies have shown that the majority of N in vetch— >70% when grown in a biculture with rye —comes from biological N fixation and is thus not dependent on residual soil N (Brainard et al., 2012; Poffenbarger et al., 2015b; Perrone et al., 2020). Including legumes that fix large amounts of N has ecological and agronomic importance, but it is not a common practice in this region to allow vetch to grow late into spring. In part, hesitance to allow hairy vetch to accumulate large amounts of biomass stems from concerns over management in tillage-based systems, as the viny material can interfere with equipment.

Conditions at each site explain some of the variability observed between total biomass and the proportion of rye and vetch. Far below average precipitation in May at RRF likely led to lower rye biomass levels, despite higher GDD than UNH. It is also possible that differences in establishment methods (broadcast vs. drill), dry conditions, and late emergence at RRF led to lower populations, although this was not quantified. Including population density will be an essential component of refining rye-vetch growth models in the future.

Vetch biomass appears to have been affected by lower GDD at UNH. This postulation is supported by the fact that vetch was less mature at all termination dates at UNH compared to RRF. Furthermore, the quantity of vetch regrowth following RC demonstrates that vetch had not reached peak biomass by T3. Linear growth models developed for hairy vetch in monoculture predict 410-540 kg ha^{-1} biomass for each 100 GDD accumulated (Teasdale et al., 2004; Mirsky et al., 2017). However, on the low end of GDD such as the conditions in our experiment (<1200 GDD), these models are far less accurate (Mirsky et al., 2017; Perrone et al., 2020). Furthermore, the severity of winter conditions, in addition to accumulated GDD, affects the spring vigor and growth patterns of hairy vetch genotypes (Kucek et al., 2019). Data from our experiment suggest that additional efforts to model rye and vetch growth in northern climates with short growing seasons and cold winters are necessary to understand and maximize N-related ecosystem services.

Cover crop quality (C:N ratio)

Overall C:N ratio of the cover crop mixture may be less important for determining decomposition dynamics and subsequent N availability than the C:N ratio of individual species and the ratio of those species to one another. Poffenbarger et al (2015a) demonstrated that N was released from hairy vetch residue independent of the winter rye residue with which it was mixed. While we did not test decomposition kinetics, the combined results from litter bags at both sites and soil mineral N from UNH shed some light on the decomposition of cover crop material from the three termination times and how this affects N-related ecosystem services.

Residue decomposition (litter bags)

Greater C and N retention in litter bags at later termination times—despite higher thermal units and equal (RRF) or greater (UNH) soil moisture—suggest that something about the cover crop material itself was more resistant to decomposition. C:N ratios of the overall material do not explain the results, given that the C:N ratio of the litter bag material was 30 at T2 and T3 at UNH yet we observed differences in C and N retention. It is possible that individual plant components (e.g., rye stems) drove this effect. Decomposition of cover crop residue slows with increasing hemicellulose, lignin, phenolic content (Ranells and Wagger, 1996). Lower microbial biomass in T3 at the conclusion of the experiment at UNH suggests that above and belowground litter quality may have had an effect on microbial activity, resulting in greater C and N retention.

It is also possible that small differences in total dry matter in the litter bags (Table 4.2) had an effect on the proportion of material that was either in contact with the soil or exposed to the elements, slowing C and N losses (Halde and Entz, 2016). The phenomenon of greater dry matter with later termination dates was more pronounced in the actual cover crop biomass than it was in the litter bag contents, but our coarse mulch measurements were not sufficient to detect effects of termination time on cover crop decomposition, nor would it have been possible to parse the effects of biomass quantity vs. quality.

There are multiple explanations for why tarping could reduce C and N losses. Tarping excludes precipitation, which could slow leaching of water-soluble C and N compounds from cover crop tissue. The proportion of water soluble N compounds in cover crops can exceed 30% of total N (Kuo and Sainju, 1998), and multiple experiments have shown that cover crop material left exposed on the soil surface can lose ~50% of its N within the first 30 days (Poffenbarger et al., 2015a; Halde and Entz, 2016; Sievers and Cook, 2018). Exposed material is also subject to UV radiation, which can accelerate mass loss via photodegradation (Henry et al., 2008; Baker and Allison, 2015). Data from tarping experiments in New York showed that tarping either had no effect on the percent cover of oat cover crop residue or resulted in higher percent cover compared to a no tarp control (Rylander et al., 2020a).

Lounsbury et al. (2020) observed in an extremely dry season that black tarps accelerated mulch loss from cover crops compared to a no tarp control and suggested that the thermal and moisture regime may have been more favorable for microbial activity. Tarping could also have the opposite effect in wetter conditions if tarps change atmospheric conditions and limit oxygen concentrations. Microbial biomass data from the conclusion of this experiment indicate that if there are effects of tarping on microbial biomass, they are short-lived. This does not exclude the possibility that tarping has an effect on microbial activity, however. Microbial biomass and activity change over short temporal scales in agricultural soils (Liang et al., 2011; Jat et al., 2020) and this end-of-season measurement was not intended to asses mid-term (i.e. >30 days), not immediate effects of tarping.

The continued effect of termination time, but not termination method, on litter C and N losses suggests that while the effects of cover crop biomass quality have longer-term effects, the effects of tarping are short-lived.

Soil mineral N

Higher NO_3^{-1}-N in the longer duration tarp treatments (Figure 4.7) suggest that oxygen was not limited. Because tarps exclude precipitation, N mineralized under tarps is not subject to leaching, and NO_3^{-1}-N accumulation under tarps has been observed in previous studies (Rylander et al., 2020a). Greater net N mineralization for the 20d and 30d treatments at T3 than T2 and T1 is likely a response to higher temperatures, but may also be a result of higher total N inputs from cover crop residue. Even if a larger fraction of N is retained in cover crop residue at later termination dates and with longer tarp durations, it is possible that the total quantity of N mineralized from cover crop residues is still greater than earlier termination times with shorter tarp durations.

Tradeoffs

Termination method

Cover crop mulch-based systems are an important adaptive strategy in the face of climate change, but implementation must be feasible and the benefits substantial for farmers to adopt them. The choice of termination method carries tradeoffs. Mechanical termination is inflexible with respect to timing and requires sufficient cover crop biomass to suppress weeds adequately, which can be hard to achieve in short growing seasons (Halde et al., 2017). Our data reinforce this. Improved cover crop growth models in northern climates, changes to agronomic management, and cover crop breeding may increase the feasibility and predictability of mechanical termination, but it is currently not reliable when used as the sole method of termination (Wallace et al., 2017).

This leaves herbicides and tarps as two currently viable strategies to terminate cover crops for *in situ* mulch. Herbicides are commonly used to terminate cover crops and have the advantages of being very effective and feasible on all scales. However, herbicides have detrimental effects on the environment and extensive use has led to herbicide resistant weeds, bringing their continued efficacy into question (Mortensen et al., 2012; Davis and Frisvold, 2017). Cover crops can mediate some of the risk of herbicide resistance, however, by reducing selection pressure (Bunchek et al., 2020). Thus, the practice of using high-biomass cover crops and herbicides is an integrated weed management tactic that moderates the detrimental effects of herbicides with other environmental and agronomic benefits. Herbicides are not permitted for certified organic producers, however.

Tarps, while permitted for certified organic production, also carry substantial tradeoffs. Microplastics from agricultural plastic use are considered a ‘contaminant of emerging concern’ in soils and water (Chae and An, 2018; Lambert and Wagner, 2018). The vast majority of agricultural plastic use involves single-use plasticulture mulch (Steinmetz et al., 2016), and there is a question of whether tarp use replaces this practice or represents a new use of plastic. Biodegradable plastics hold promise, but persistent micro and nanoparticles derived from additives have been observed after degradation of these products (Sintim et al., 2019, 2020). Many small farmers do not otherwise have equipment to practice intensive cover cropping or reduced tillage (O'Connell et al., 2014; Lowry and Brainard, 2017), and tarps have a low barrier to entry because they are inexpensive and have many uses on the farm.

Given the significant tradeoffs associated with these termination methods—despite their efficacy—continued research into other methods for cover crop termination and additional weed suppression for no-till systems is necessary. Other approaches include alternative occultation materials, bioherbicides (Cordeau et al., 2016), and cut and carry mulch systems (Mulvaney et al., 2017). Furthermore, cover crop breeding and improved agronomic practices may make mechanical termination a viable strategy in short-season climates.

Termination time and tarp duration

Cash crop planting date drives many cover crop management decisions, as allowing cover crops to grow can create additional management complexity and delay planting (Schipanski et al., 2014). Planting date constraints are greater for grain crops, which require a longer growing season than many vegetable crops. However, direct market vegetable producers need to have products throughout the season, so delaying planting has economic ramifications. Even with these constraints, crop planting date is not fixed. Short-season genetics allow for delayed crop planting without yield reductions, and are a promising strategy for grain farmers to use more intensive cover cropping on a portion of their land while staggering field work (Groff, 2015). For vegetable crops, different crop growth periods, successional plantings, shorter-season varieties, and later transplanting (i.e., plants grown in larger pots) create opportunities for delayed crop planting within diversified rotations. Farmers have to decide how to divide the limited thermal units within their growing season based on markets, crop requirements, and their valuation of ecosystem service tradeoffs.

Delayed cover crop termination increases cover crop biomass, which is correlated to short and long-term changes in soil organic matter (McClelland et al., 2020). Biomass is also correlated to weed suppression (Finney et al., 2016; Osipitan et al., 2019), but our results show that weed suppression at the same cover crop biomass level (i.e. termination time) varies with termination method, perhaps mediated by effects on mulch. Glyphosate application was highly effective at suppressing weeds across all cover crop biomass levels, while the effects of tarp duration on weed suppression were more pronounced when cover crop biomass levels were lower (e.g., RRF T1). Altering the time of cover crop termination or tarp duration can also select for or suppress certain weed species. This effect is not captured in tradeoffs that just assess weed biomass, but should be considered as part of an integrated weed management strategy so as not to create dominance by problematic weeds (MacLaren et al., 2020)

In previous research, effective weed suppression by cover crop biomass has come at the expense of N availability and crop yields (Leavitt et al., 2011; Wallace et al., 2017; Hefner et al., 2020b). This can be a result of insufficient N mineralization (or even N immobilization) as well as preemptive competition from cover crops that effectively scavenge available N early in the season (Thorup-Kristensen et al., 2003; Hefner et al., 2020a). Early termination can ameliorate this effect, by allowing adequate time for cover crop decomposition prior to establishing cash crops. Tarping may enhance the effects of early termination on N mineralization compared to other termination methods by preventing leaching, but absence of precipitation may also prevent leaching of soluble compounds from cover crop tissue itself, thereby slowing decomposition.

However, the 60 day litter bag data from UNH show this effect is short-lived. Greater total N accompanied by slower decomposition, as in T3, may be advantageous for synchronizing season-long N supply and demand from growing crops (Poffenbarger et al., 2015a; Lacey et al., 2020).

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CONCLUSIONS

The research in this dissertation follows the course of an idea to use tarps (occultation) to terminate high-residue cover crops for no-till production from proof-of-concept to optimization. Growing cover crops and reducing tillage are critical management strategies for agriculture to adapt to climate change, but myriad reasons make integrating these practices into production systems challenging. This research fills knowledge gaps that will enable more informed decision-making for different groups of farmers when it comes to cover crops and reduced tillage. Most obviously, this research applies to small-scale organic farmers in areas with short-growing seasons like New England. However, it is also relevant for small-scale farmers in other climates who may not face the short-season challenge of adequate cover crop biomass production, but still face the challenge of terminating cover crops and suppressing weeds sufficiently. The concept of occultation as a weed management strategy is currently not scalable because of equipment limitations, and materials available present significant environmental tradeoffs because they are made of plastic. However, there is tremendous potential for alternative materials that operate by the same mechanism (light exclusion) but do not have the same tradeoffs with respect to manufacturing, disposal, and pollution.

The data from these experiments regarding cover crop termination time and resulting biomass quantity and quality are important for all farmers in this region who are interested in growing cover crops but must weigh the tradeoffs of when to terminate them. These management decisions are increasingly complex in the face of a changing climate with altered growing seasons and precipitation patterns. By quantifying tradeoffs of cover crop termination time and tarp duration using growing degree days (Chapters 2 and 4), this work promotes the use of meaningful units to discuss these tradeoffs that has broad applicability to different cropping systems and regions. Data from Chapter 3 suggest that timing of cover crop management is important not only with respect to biomass production, but for managing weed species based on periodicity. The ability to predict weed community composition is another reason why using meaningful units such as growing degree days is critical to future research. Chapter 3 also shows that although cover crop mulch is highly effective at suppressive weeds, it is a strong filter, suggesting that this strategy—like most ecological weed management techniques—is best used in conjunction with multiple strategies that target different weed traits. Only with a holistic approach to weed management will we be able to tackle the challenges of climate change and herbicide resistance in the future.

APPENDIX: AERIAL IMAGE OF EXPERIMENT

Photo: Alena Warren.

Aerial image of experiment from Chapters 3 and 4 at University of New Hampshire. Image taken June 26, 2019.