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Evaluating high-resolution optical and thermal reflectance of maize interseeded with cover crops across spatial scales using remotely sensed imagery

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Abstract

We evaluated the optical and thermal reflectance of maize (*Zea mays* L.) interseeded with cover crops using remotely sensed canopy temperature and multispectral imagery. In 2017 and 2018 annual ryegrass (*Lolium multiflorum* Lam.), crimson clover (*Trifolium incarnatum* L.), oilseed radish (*Raphanus sativus* L.), and a mixture of annual ryegrass and crimson clover were interseeded in maize at V3 and V6 at three different cover crop seeding rates in small research plots at two experimental farm sites within the network of Michigan State University. The same cover crop species were interseeded in maize at V3 and V6 at a single seeding rate in on-farm replicated strip trials and also a full-scale field trial at five locations in Michigan. Canopy temperature and multispectral reflectance were remotely measured 10–12 times throughout each season at all sites using fixed wing aircraft at 1-m spatial resolution. Optical and thermal reflectance were also measured remotely using an unmanned aerial vehicle (UAV) with 2-cm spatial resolution three times during the growing season at the small plot sites. Normalized difference vegetation index (NDVI) and normalized difference red-edge (NDRE) were calculated for each of the experimental sites. No significant differences were detected between the interseeded treatments and control with regards to the optical and thermal reflectance and maize grain yield. Variability at field scale was due to inherent differences and not caused by the interseeding treatments.

1 | INTRODUCTION

The presence of cover crops in the U.S. Midwest maize (*Zea mays* L.) and soybean (*Glycine max* L.) fields has shown to be a beneficial practice from an environmental benefits viewpoint. Cover crops reduce water runoff, increase infiltration, improve soil organic matter and overall soil health, reduce soil erosion, nitrate leaching and suppress weeds (Daryanto, Fu, Wang, Jacinthe, & Zhao, 2018; Nichols et al., 2020). Despite the numerous environmental benefits, only 10% of the U.S. Midwest fields are planted with cover crops (Runk, Khoury, Ewing, & Kantar, 2020). This may be due to the cost associated with their implementation and the short-term economic returns perceived by the farmers, rather than the longer-term economic benefits of regenerating soils and improving yields (Baker & Griffis, 2009; Plastina, Liu, Miguez, & Carlson, 2018; Strock, Porter, & Russelle, 2004). The unfavorable fall

Abbreviations: DAI, days after interseeding; KBS, Kellogg Biological Station; MSU, Michigan State University; MSUAF, MSU Agronomy Farm; NDRE, normalized difference red-edge; NDVI, normalized difference vegetation index; SOM, soil organic matter; SVREC, Saginaw Valley Research and Extension Center; UAV, unmanned aerial vehicle.

and winter climate conditions in the U.S. Midwest negatively affects the cover crop establishment and growth, which may also add to the list of reasons of low adoption of cover crops by farmers. Summer cereals and leguminous cover crops can be seeded following winter wheat (*Triticum aestivum* L.) harvest in mid-summer, but winter cereals are often the only option for a cover crop seeding after soybean or maize harvest in the fall (Baker & Griffis, 2009). Advantages for establishing leguminous cover crops, like red clover (*Trifolium pratense* L.), include the likelihood of enhancing soil nitrogen availability to the subsequent corn crop (Gentry, Snapp, Price, & Gentry, 2013). This makes the establishment of cover crops, with more than just cereals, a vital goal for sustainable maize production.

Interseeding cover crops in maize during the early vegetative growth stages is an opportunity to establish a grass or broadleaf cover crop and add rotational diversity to improve overall system productivity (McDaniel, Tiemann, & Grandy, 2014; Tiemann, Grandy, Atkinson, Marin-Spiotta, & McDaniel, 2015). Researchers have shown that cover crops can be interseeded in maize without reducing grain yield (Brooker, Renner, & Basso, 2020; Brooker, Renner, & Sprague, 2020). Annual ryegrass (*Lolium multiflorum* Lam.) and red clover interseeded after the V2 maize growth stage (Abendroth, Elmore, Boyer, & Marlay, 2011) did not reduce grain yield in Pennsylvania, Maryland, and New York (Curran et al., 2018). Red clover interseeded in maize at the V5–V7 growth stages but did not reduce grain yield in Michigan (Baributsa et al., 2008). Noland et al. (2018) found that cover crops interseeded with a drill, broadcast, and broadcast with incorporation at the V7 growth stage of maize did not reduce grain yield in Minnesota.

The mechanisms by which cover crops potentially compete with cash crops have not been the focus of previously published small plot research. In farmer's fields where soil type and topography vary, cover crops could compete with maize for water and nutrients. In intercropping experiments, sole maize usually yielded more than maize intercropped with soybean (Ren, Liu, Wang, & Zhang, 2016). However, where pea (*Pisum sativum* L.) (Chen et al., 2018) and wheat (Yang, Huang, Chai, & Luo, 2011) were intercropped with maize, water use efficiency increased, and total crop yields increased compared with sole crops. These dynamic systems involve complex biotic and abiotic processes that remain difficult to discern within a single study. Thermal and optical remote sensing can play a critical role in separating water stress from N stress and presence of diseases (Hatfield, Cryder, & Basso, 2020). Continued research of these processes is necessary to enhance the knowledge of a cover crop's effect on the subsequent main crop within the agronomic system.

Remote sensing is an important tool for detecting crop stress across small-plot and field-scale cropping systems (Basso, Cammarano, & De Vita, 2004; Basso, Fiorentino, Cammarano, & Schulthess, 2016). Thermal and multispectral imaging allows researchers to monitor crop growth throughout the growing season (Maestrini & Basso, 2018). Normalized difference vegetation index (NDVI) (Tucker, 1979), which is the difference between near-infrared light reflected by leaves and red light which is highly absorbed by leaves, is correlated with photosynthetic activity (Maestrini & Basso, 2018). Normalized difference red edge (NDRE) replaces the red band in the NDVI calculation and indicates the chlorophyll and nitrogen content of the cash crop (Cammarano, Fritzgerald, Casa, & Basso, 2014, Fitzgerald et al., 2006). Measuring canopy temperature provides an estimate of plant transpiration, which is an indicator of soil water availability and photosynthetic rate (Maestrini & Basso, 2018). Remote sensing in interseeded systems may provide insight into how cover crops influence evapotranspiration (ET), maize growth and development, and water and nutrient availability throughout the growing season. Additionally, topography, soil type, and management history vary within fields (Martinez-Feria & Basso, 2020); therefore, cover crop establishment and competitiveness with maize may also be variable across a field.

The objective of this study was to assess optical and thermal reflectance of maize interseeded with cover crops across spatial scales using remotely sensed imagery maize. The study was performed at three different spatial scales: small research plots, long-farm strip trials, and full field-scale trials.

Core Ideas

- Optical and thermal reflectance did not show any differences in cover crops treatments.
- Interseeded cover crops did not affect maize growth and yield.
- At field scale, the inherent spatial variability had greater impact than interseeded cover crop treatments.

2 | MATERIALS AND METHODS

2.1 | Experimental sites and management

Experimental field trials were conducted at seven field locations across the state of Michigan in 2017 and 2018 (Figures 1 and 2). Two small-trial research plot experiments were established at the research farms of Michigan State University (MSU): MSU Agronomy Farm (MSUAF) and Saginaw Valley Research and Extension Center (SVREC). A larger strip-trial was established at the Kellogg Biological Station (KBS) on two fields: 30-2 and B1. A full-scale field

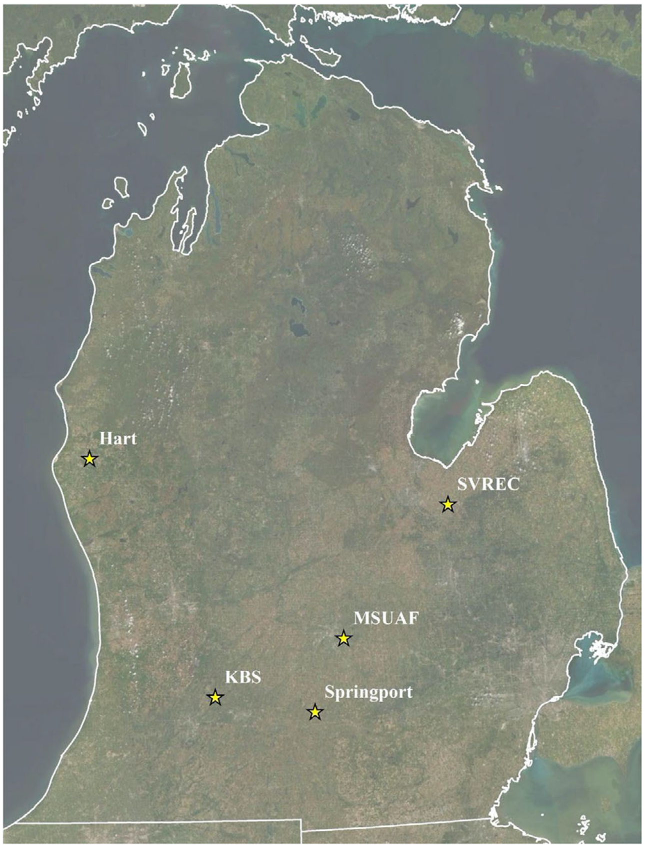

FIGURE 1 Locations of field experiments in the state of Michigan

trial was established by two cooperating farmers located in Hart and Springport. Two different fields were included in Springport: Springport (2017) and Springport (2018).

2.2 | Small-trial research fields

The MSUAF trial in East Lansing, MI (42.7100 N, 84.4663 W) was established on an Aubbeenaubbee (fine-loamy, mixed, active, mesic Aeric Epiaqualf)–Capac (fine-loamy, mixed, active, mesic Aquic Glossudalf) sandy loam in 2017 and the SVREC trial in Richville, MI (43.3952 N, −83.6831 W) was established on a Tappan (fine-loamy, mixed, active, calcareous, mesic Typic Epiaquoll)–Londo (fine-loamy, mixed, semiactive, mesic Aeric Glossaqualf) loam in 2018. Soil organic matter was 3.1% and MSUAF in 2017 and 3.0% at SVREC in 2018. The experimental design was a split-plot with four replications; cover crop species was the main plot and the combination of cover crop seeding rate and the time of interseeding was the subplot. Plot size was 3 m wide and 12 m long. These experimental plots were chisel plowed in the fall prior to the experiment and tilled with a soil finisher in the spring just prior to planting. Nitrogen as urea (CH_4N_2O) was broadcast prior to tillage and incorporated at a rate of 155 kg ha^{-1}, and an additional 32 kg ha^{-1} of N as urea and ammonium nitrate (NH_4NO_3), P as P_2O_5, and K as K_2O were applied in a 5 by 5-cm band as starter fertilizer at planting. At the SVREC site, the tillage included a disc ripper in the fall prior to the experiment and a triple K in the spring prior to planting. Nitrogen as CH_4N_2O at 157 kg ha^{-1} was applied prior to planting. At each small research trial, glyphosate [N-(phosphonomethyl) glycine]-resistant maize was planted in late April to mid-May using a four-row planter in 76-cm rows (Table 1). Seeding depth was 3.8 cm at MSUAF and 5 cm at SVREC and the seeding rate in all site-years was 79,000 seeds ha^{-1}. Weeds were controlled the week prior to maize planting and when maize reached the V3 and V6 growth stages glyphosate (0.84 kg a.e. ha^{-1}) + ammonium sulfate (AMS) were applied.

2.3 | Strip-trial research fields

The KBS fields were established as a strip-trial with strips 294.1 m long and 4.6 m wide in field 30-2 and 73.2 m long by 4.6 m wide in field B-1. Field 30-2 (42.4146 N, 85.3934 W) was not tilled and field B-1 (42.4029 N, 85.3760 W) was chisel plowed in the fall and tilled with a soil finisher in the spring. Both fields received dairy manure; field 30-2 received a solid application of 16.8 Mg ha^{-1} in the spring of 2017 and field B-1 received 46,769 L ha^{-1} in the fall of 2016. Cover crops were interseeded with a Gandy Air Seeder (Gandy Company) at rates of 0.5, 1, and 2 times the standard seeding rates per Brooker, Renner, and Basso (2020).

2.4 | On-farm trial research fields

The on-farm trial fields at Springport (42.3822 N, 84.7041 W and 42.3240 N, 84.6833 W) and Hart (43.6815 N, 86.2701 W) were selected based on farmer interest and ability to broadcast interseed cover crops; farmers made all field and crop management decisions except for the cover crop species and time of interseeding. For these fields, annual ryegrass, oilseed radish (*Raphanus sativus* L.), and crimson clover (*Trifolium incarnatum* L.) were interseeded at a single seeding rate (Table 2) at the V3 and V6 maize stages. Glyphosate-resistant maize was planted in 76-cm rows all in late May at populations ranging from 69,160 to 83,980 seeds ha^{-1} for all fields. Weeds were managed with tillage or a burndown herbicide application prior to planting maize. Dates for the V3 seeding ranged between 1 June and 19 June; V6 seeding dates ranged between 14 June and 5 July (Table 2). Interseeded strip width ranged from 6 to 40 maize rows based on the width of the interseeder; row length ranged from 30 to 300 m based on farmer field dimensions and preferences. At the Springport 2017 and 2018 sites, a single strip, 300 m in length, was interseeded for each species by seeding rate

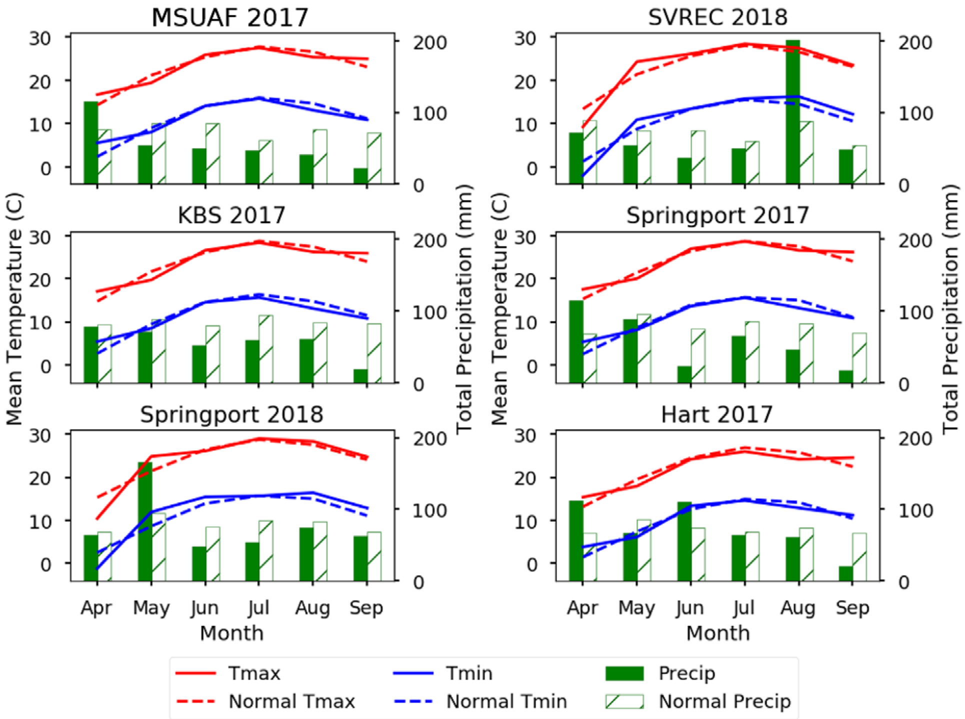

FIGURE 2 Average monthly maximum and minimum temperature and total precipitation for the duration of the growing season reported at each field location for the two studied years

TABLE 1 Maize planting, harvest dates, and cover crop seeding dates for each site-year

Site-year	Maize planting	Interseed timing		Maize harvest
		V3	V6	
MSUAF 2017	15 May	6 June	23 June	13 Oct.
SVREC 2018	9 May	5 June	18 June	16 Oct.
KBS 30-2 (2017)	8 May	1 June	19 June	1 Nov.
KBS B1 (2017)	28 Apr.	1 June	19 June	12 Oct.
Springport 2017	31 May	19 June	2 July	8 Nov.
Springport 2018	26 May	14 June	21 June	30 Oct.
Hart 2017	13 May	5 June	16 June	13 Oct.

combination. Recommended seeding rates were 16.8, 22.4, and 11.2 kg ha^{-1} for annual ryegrass, crimson clover, and oilseed radish, respectively; rates varied slightly based on farmer preferences (Table 2). Strips were replicated and randomized either three or four times depending on spatial constraints and no cover control strips were always included. Cover crop biomass measurements were taken on the larger-scaled field trials (Brooker, Renner, & Basso, 2020); however, remote sensing was used to assess the impact of cover crops interseeded into maize across the large replicated plots within the field sites. Maize grain at the on-farm trials were harvested using a combine with a dedicated yield monitor. The data was cleaned and exported for the trial design using geoprocessing tools found in ArcPy (ESRI).

2.5 | Cover crop information

Cover crop species included annual ryegrass, oilseed radish, and crimson clover with NitroCoat seed coating (Smith Seed Services), and annual ryegrass + crimson clover in a 25:75 mixture by weight (La Crosse Seed LLC). Cover crops were interseeded between the first and fourth maize rows using a hand spreader at the V3 maize growth stage and again at the V6 maize growth stage following the glyphosate application at MSUAF and SVREC. Interseeding rates were 0.5, 1, and 2 times the standard seeding rate. Standard seeding rates for single species fell within ranges recommended by Sustainable Agriculture Research and Education (SARE) and were 17 kg ha^{-1} for annual ryegrass, 11 kg ha^{-1} for oilseed radish,

TABLE 2 Location, field management, and cover crop interseeding information for on-farm experiments conducted in Michigan in 2017 and 2018

Location	Year	Lat./Long.	Major soil type	pH	Soil organic matter	Tillage	AR	CC	OR
					%			kg ha^{-1}	
MSUAF	2017	42.7100 N, 84.4663 W	Aubbeenaubbee-Capac sandy loam	6.5	1.5	Yes	Varied	Varied	Varied
SVREC	2018	43.3952 N, 83.6831 W	Tappan-Londo loams	7.5	5.1	Yes	Varied	Varied	Varied
KBS 30-2	2017	42.4146 N, 85.3934 W	Kalamazoo loam	6.6	2.0	No	33.6	33.6	22.4
KBS B1	2017	42.4029 N, 85.3760 W	Kalamzaoo loam	5.9	1.8	Yes	33.6	33.6	22.4
Springport (2017)	2017	42.3822 N, 84.7041 W	Riddles sandy loam	5.9	1.6	No	16.8	22.4	11.2
Springport (2018)	2018	42.3240 N, 84.6833 W	Riddles sandy loam	6.2	1.8	No	8.4	11.2	7.2
Hart 2017	2017	43.6815 N, 86.2701 W	Tekenink loamy sandy	6.6	1.7	Yes	16.8	22.4	11.2

Note. AR = annual ryegrass; CC = crimson clover; OR = oilseed radish.

TABLE 3 Unmanned aerial vehicle (UAV) and AirScout flyover dates for each site-year

MSUAF 2017	SVREC 2018	KBS 30-2	KBS B-1	Springport 2017	Springport 2018	Hart 2017
AirScout dates						
29 May	7 May	29 May	29 May	12 Apr.	7 May	30 May
16 June	23 May	16 June	16 June	8 May	23 May	16 June
27 June	6 June	28 June	28 June	26 May	6 June	27 June
6 July	17 June	6 July	6 July	15 June	18 June	7 July
18 July	1 July	18 July	18 July	29 June	1 July	17 July
31 July	8 July	31 July	31 July	6 July	8 July	1 Aug.
20 Aug.	18 July	20 Aug.	20 Aug.	18 July	17 July	20 Aug.
5 Sept.	3 Aug.	6 Sept.	6 Sept.	31 July	3 Aug.	6 Sept.
21 Sept.	22 Aug.	20 Sept.	20 Sept.	19 Aug.	22 Aug.	21 Sept.
	12 Sept.			5 Sept.	14 Sept.	
	3 Oct.			20 Sept.	4 Oct.	
	16 Oct.				16 Oct.	
UAV dates						
21 June	15 June					
30 June	6 July					
14 July	29 July					
18 July						

22 kg ha^{-1} of coated seed for crimson clover (Clark, 2007). The standard mixture seeding rates were 6 and 17 kg ha^{-1} of annual ryegrass and crimson clover, respectively (Kramberger, Gselman, Janzekovic, Kaligaric, & Bracko, 2009). Cover crop seeding dates were in May and June and depended on maize planting date and growth stage at each location (Table 1). Two control plots were included that were not seeded with cover crops: one weed-free plot and one weedy plot where weeds were not controlled. In both MSUAF and SVREC, cover crop biomass was measured using 0.25 m^2 quadrats in October prior to corn harvest and in the following April prior to maize planting. Results are published in Brooker, Renner, & Sprague (2020). Maize yields were harvested in the center two rows of each four-row plot

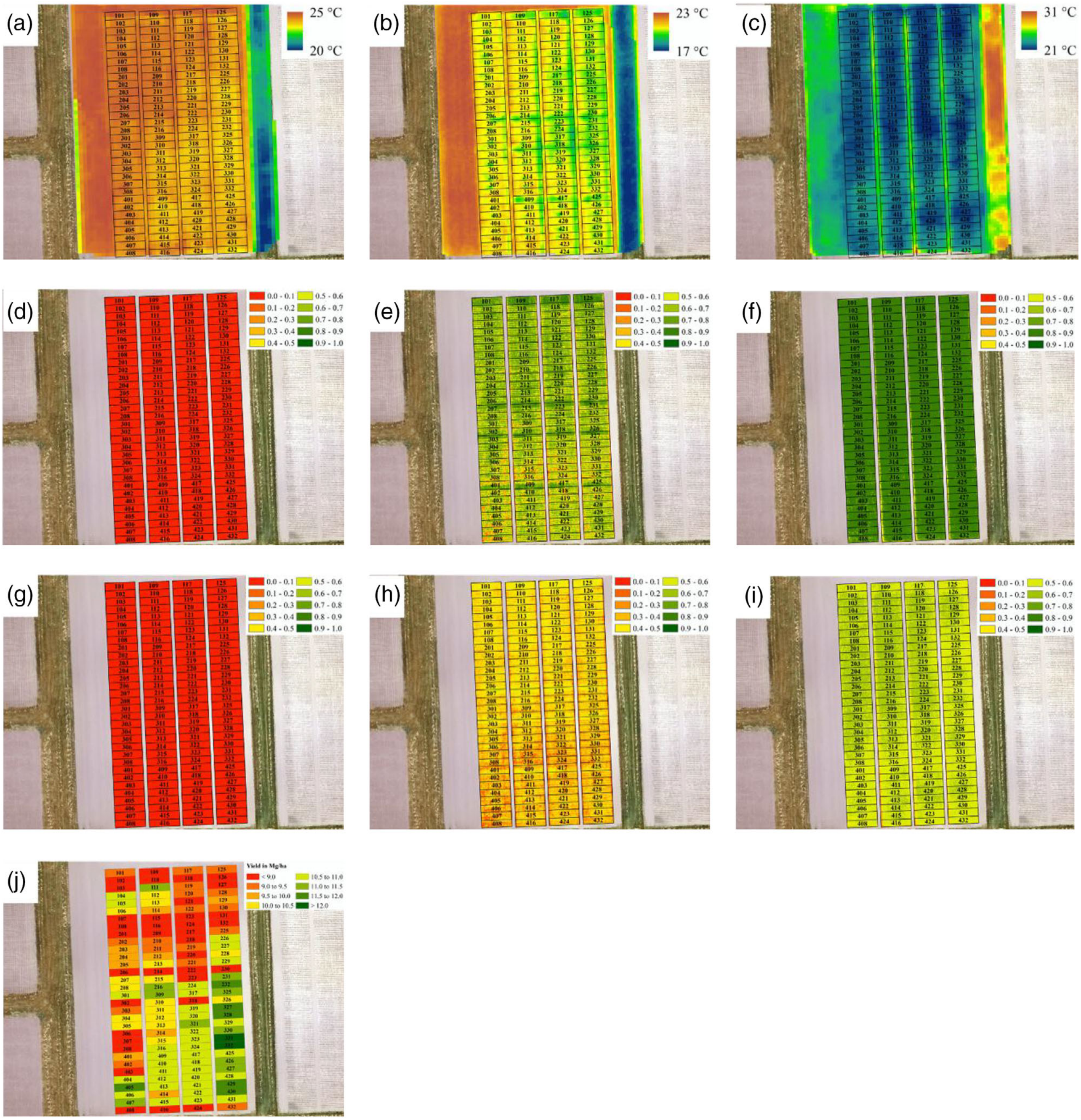

FIGURE 3 Imagery from MSUAF in 2017. (a) Thermal image on 16 June, (b) thermal image on 27 June, (c) thermal image on 20 August, (d) normalized difference vegetation index (NDVI) image on 12 June, (e) NDVI image on 30 June, (f) NDVI image on 16 August, (g) normalized difference red-edge (NDRE) image on 12 June, (h) NDRE image on 30 June, (i) NDRE image on 16 August, (j) final yield map

using a small plot combine and the weights were reported at 15% moisture content. Cover crop biomass was also measured at on-farm locations and results published in Brooker, Renner, and Basso (2020). Briefly, cover crops interseeded at V3 stages had better establishment and yield higher biomass than the cover crops interseeded at V6 for all the sites, except one (Clayton). The interseeded biomass harvested at harvest varied widely across sites. To report again results presented in Brooker, Renner, and Basso (2020) annual rye biomass ranged from 27 kg ha^{-1} in Clayton to 652 in Hillman, while oilseed radish ranged from 65 kg ha^{-1} of Clayton to 1,103 kg ha^{-1} of Hickory Corners B.

TABLE 4 Means of remotely sensed canopy temperature at KBS 30-2 (2017) compared between cover crop species and interseed timing from each image date. Days after planting (DAP) of maize is noted within each column

Cover crop species	Interseed timing	29 May,[a] 21 DAP	16 June[a] 39 DAP	28 June,[a] 51 DAP	6 July,[a] 59 DAP	31 July,[a] 84 DAP	29 Aug.,[a] 113 DAP	6 Sept.,[a] 121 DAP	20 Sept.,[a] 135 DAP
Control, 6-species mix	V6	13.713.6	28.028.4	22.722.8	27.427.6	24.824.8	22.923.0	21.521.5	15.115.0
Crimson clover	V3	13.7	28.2	22.6	27.1	24.5	22.8	21.4	15.1
Crimson clover	V6	13.7	28.4	22.8	27.6	24.7	22.9	21.3	15.0
Mixture	V3	13.7	27.5	22.6	27.4	24.5	22.7	21.4	15.1
Radish	V3	13.8	26.7	22.7	27.1	24.3	22.8	21.4	14.9
Radish	V6	13.7	28.2	22.6	27.2	24.6	22.9	21.3	15.1
Royal ryegrass	V6	13.7	28.0	22.7	27.6	24.8	22.9	21.3	15.0
Ryegrass	V3	13.7	27.9	22.5	27.2	24.6	22.7	21.4	15.2
Ryegrass	V6	13.7	28.7	22.8	27.9	24.9	22.9	21.1	14.9
Winter hardy	V6	13.7	27.8	22.7	27.3	24.7	22.8	21.4	15.1
Winter kill	V6	13.7	27.9	22.7	27.4	24.7	22.9	21.5	15.1

[a]No significant differences of means within each date reported from ANOVA using $\alpha = .05$.

TABLE 5 Means of remotely sensed plant reflectance (NDVI) at SVREC (2018) compared between cover crop species and interseed timing from each image date. Days after planting (DAP) of maize is noted within each column

Cover crop species	Interseed timing	15 June,[a] 38 DAP	6 July,[a] 59 DAP	29 July,[a] 81 DAP
Annual ryegrass	Untreated control	0.3406	0.8704	0.9135
	V3	0.3431	0.8728	0.9124
	V6	0.3367	0.8704	0.9126
	Weed free	0.3501	0.8766	0.9186
Crimson clover	Untreated control	0.3500	0.8801	0.9170
	V3	0.3534	0.8769	0.9162
	V6	0.3369	0.8688	0.9130
	Weed free	0.3394	0.8732	0.9125
Mix	Untreated control	0.3418	0.8692	0.9112
	V3	0.3529	0.8695	0.9131
	V6	0.3515	0.8784	0.9150
	Weed free	0.3437	0.8723	0.9157
Tillage radish	Untreated control	0.3406	0.8704	0.9135
	V3	0.3431	0.8728	0.9124
	V6	0.3367	0.8704	0.9126
	Weed free	0.3501	0.8766	0.9186

[a]No significant differences of means within each date reported from ANOVA using $\alpha = .05$.

2.6 | Remote sensing acquisition and vegetation index calculation

A commercial airborne image company, AirScout, Inc., flew 9–12 times from May through October each year (Table 3). Plant surfacetemperature was collected from both the small research plots and the on-farm strip trial sites using a plane mounted FLIR thermal sensor. A proprietary index, advanced difference vegetation index (ADVI), was also included in their imagery. The spatial resolution of airborne imagery was

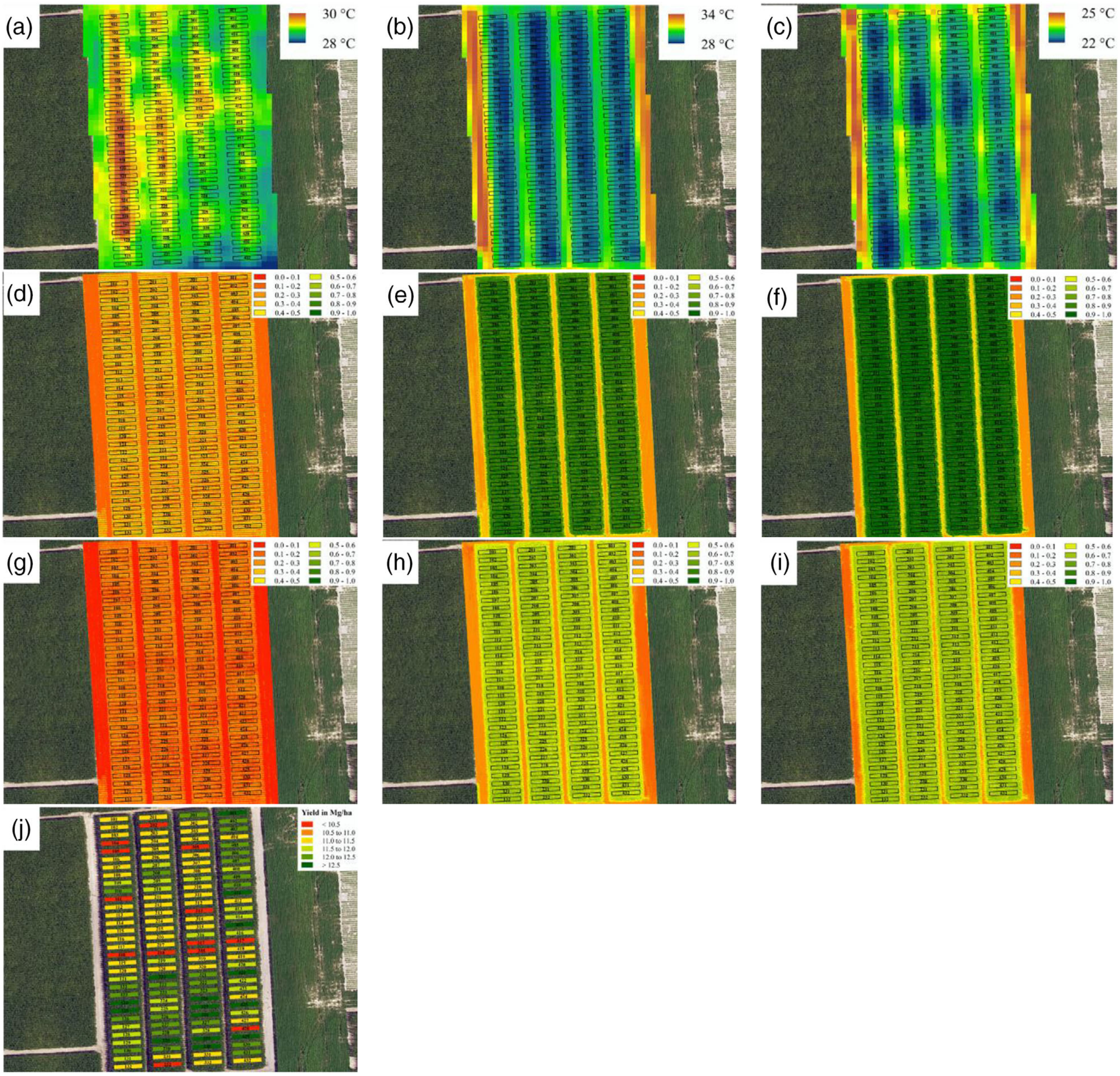

FIGURE 4 Thermal imagery at SVREC field in 2018. (a) thermal image on 17 June, (b) thermal image on 8 July, (c) thermal image on 3 August, (d) normalized difference vegetation index (NDVI) image on 5 June, (e) NDVI image on 6 July, (f) NDVI image on 29 July, (g) normalized difference red-edge (NDRE) image on 5 June, (h) NDRE image on 6 July, (i) NDRE image on 29 July, (j) final yield map

resampled to 0.5 m for the optical and ADVI and resampled to 1 m for the thermal. Additional measurements of plant reflectance were captured using a MicaSense® RedEdge3 (MicaSense, Inc.) multispectral camera mounted on an unmanned aerial vehicle DJI Matrice 100. Multispectral imagery was captured three times during the growing season from June to July at the small research plot sites only (Table 3). The spatial resolution of unmanned aerial vehicle (UAV) imagery depends on each flight's altitude and is approximately 2 cm for visible, 4 cm for multispectral, and 5 cm for thermal. These reflectance data were used to calculate two vegetation indices: NDVI (Equation 1) and NDRE (Equation 2) using the following equations:

$$\mathrm{NDVI} = \frac{\mathrm{NIR}_{780} - \mathrm{RED}_{660}}{\mathrm{NIR}_{780} + \mathrm{RED}_{660}} \tag{1}$$

$$\mathrm{NDRE} = \frac{\mathrm{NIR}_{780} - \mathrm{REDEDGE}_{715}}{\mathrm{NIR}_{780} + \mathrm{REDEDGE}_{715}} \tag{2}$$

Remotely sensed imagery from both airborne and UAV platforms were georeferenced using ArcMap 10.7. The Spatial Analyst toolbox was used to obtain average plot temperature,

TABLE 6 Means of remotely sensed plant reflectance (NDVI) at MSUAF (2017) compared between cover crop species and interseed timing from each image date. Days after planting (DAP) of maize is noted within each column

Cover crop species	Interseed timing	12 June,[a] 28 DAP	21 June,[a] 37 DAP	30 June,[a] 47 DAP	19 July,[a] 66 DAP
Annual ryegrass	Untreated control	−0.1059	0.1633 A	0.6273 A	0.8431 A
	V3	−0.1127	0.1815	0.6357	0.8457
	V6	−0.1187	0.1586	0.6230	0.8431
	Weed free	−0.1217	0.1542	0.6224	0.8414
Crimson clover	Untreated control	−0.1169	0.1460	0.6070	0.8327
	V3	−0.1190	0.1665	0.6231	0.8405
	V6	−0.1227	0.1443	0.6116	0.8391
	Weed free	−0.1264	0.1361	0.6059	0.8355
Mix	Untreated control	−0.1053	0.1766	0.6368	0.8454
	V3	−0.1091	0.1813	0.6296	0.8426
	V6	−0.1215	0.1405	0.6086	0.8407
	Weed free	−0.1274	0.1334	0.6070	0.8406
Tillage radish	Untreated control	−0.1039	0.1752	0.6357	0.8478
	V3	−0.1175	0.1657	0.6313	0.8447
	V6	−0.1261	0.1314	0.6115	0.8418
	Weed Free	−0.1265	0.1317	0.6067	0.8375

[a]No significant differences of means within each date reported from ANOVA using $\alpha = .05$.

TABLE 7 Maize yields collected via combine grain yield monitor at harvest for each location

Cover crop species	Interseed timing	MSUAF	SVREC	KBS 30-2	KBS B-1	Springport 2017	Springport 2018	Hart 2017
		kg ha^{-1}						
Crimson clover	V3	10,546	11,691	12,158	10,542	10,227	11,312	11,269
	V6	10,392	11,786	11,808	10,492	9,857	11,208	12,450
Annual ryegrass	V3	10,056	11,336	12,131	10,637	10,144	10,782	11,524
	V6	10,215	11,808	11,824	10,490	10,172	11,264	11,803
Mixture	V3	10,072	11,505	11,851	10,580	N/A	N/A	N/A
	V6	10,210	11,424	N/A	N/A	N/A	N/A	N/A
Tillage radish	V3	10,381	11,451	11,685	10,706	9,900	10,973	11,478
	V6	10,818	11,181	12,294	10,417	9,989	11,201	12,215
No cover control		7,393	11,327	12,257	10,327	10,293	11,150	10,981

Note. N/A, not applicable.

average NDVI, and average NDRE for each plot at each image acquisition date.

2.7 | Statistical analyses

Data were analyzed in SAS 9.4 (SAS Institute Inc.). Canopy temperature captured via remotely sensed imagery was analyzed across all treatments and sampling dates. An initial analysis was conducted using the MIXED procedure to determine the effects of the independent variables including cover crop species, interseeding timing, seeding density, time of measurement, and all interactions on the dependent variables of plot temperature, NDVI, and NDRE. Time of measurement was considered a repeated measure for each independent variable and a compound symmetry covariance structure was used. Comparisons of least square means at $P \leq .05$ were made if F tests were significant ($P \leq .05$) for the initial

TABLE 8 Means of remotely sensed canopy temperature at Springport (2017) compared between cover crop species and interseed timing from each image date. Days after planting (DAP) of maize is noted within each column

Cover crop species	Interseed timing	15 June,[a] 15 DAP	29 June,[a] 29 DAP	6 July,[a] 36 DAP	18 July,[a] 49 DAP	31 July,[a] 62 DAP	19 Aug.,[a] 81 DAP	2 Sept.,[a] 95 DAP	5 Sept.,[a] 98 DAP
Crimson clover	V3	25.4 A	20.7 A	35.3 A	23.8 A	27.3 A	21.8 A	21.4 A	15.6 A
	V6	25.8	20.9	34.6	23.7	27.7	21.8	21.4	15.6
Radish	V3	25.6	20.8	35.0	23.8	27.9	21.9	21.4	15.6
	V6	26.0	20.7	35.7	23.7	27.8	21.9	21.4	15.5
Ryegrass	V3	25.5	20.6	35.6	23.8	27.3	21.9	21.4	15.5
	V6	25.8	20.8	34.5	23.9	26.7	21.8	21.3	15.4
No cover control		25.6	20.7	35.0	23.7	26.9	21.8	21.4	15.5

[a]No significant differences of means within each date reported from ANOVA using $\alpha = .05$.

TABLE 9 Means of remotely sensed canopy temperature at Springport (2018) compared between cover crop species and interseed timing from each image date. Days after planting (DAP) of maize is noted within each column

Cover crop species	Interseed timing	6 June,[a] 12 DAP	18 June,[a] 24 DAP	1 July,[a] 37 DAP	8 July,[a] 44 DAP	17 July,[a] 53 DAP	3 Aug.,[a] 70 DAP	22 Aug.,[a] 88 DAP	14 Sept.,[a] 111 DAP	4 Oct.,[a] 131 DAP
Crimson clover	V3	26.6 A	29.8 A	31.3 A	33.3 A	28.9 A	23.5 A	19.3 A	22.6 A	17.6 A
	V6	26.9	30.0	31.9	34.1	29.8	23.6	19.4	22.9	17.9
Radish	V3	26.6	29.6	31.5	33.6	29.1	23.5	19.3	22.8	17.8
	V6	26.8	30.1	31.6	33.7	29.7	23.5	19.3	22.6	17.5
Ryegrass	V3	26.5	29.5	31.3	34.5	29.1	23.6	19.2	22.7	18.1
	V6	26.7	29.9	31.6	33.7	29.6	23.5	19.5	22.6	17.7
No cover control		26.4	29.8	31.5	34.3	29.2	23.6	19.4	22.8	17.9

[a]No significant differences of means within each date reported from ANOVA using $\alpha = .05$.

model using *t* tests conducted by the SAS pdmix800 macro. The GLIMMIX procedure was used to complete an ANOVA of different remotely sensed indices including temperature, NDVI, and NDRE. Finally, the REG procedure was used to measure correlation of cover crop biomass and maize grain yield with canopy NDVI and NDRE. Slope was determined to be different from zero when the model was significant at $P \leq .05$. The coefficient of determination (R^2) determined the proportion of variance in cover crop biomass and grain yield explained by NDVI and NDRE.

Weather data including daily temperature and rainfall were downloaded using the Enviroweather Network hosted by MSU (East Lansing). Any years with more than 10% missing values during the growing season were removed for the

TABLE 10 Means of remotely sensed canopy temperature at Hart (2017) compared between cover crop species and interseed timing from each image date. Days after planting (DAP) of maize is noted within each column

Cover crop species	Interseed timing	16 June,[a] 34 DAP	27 June,[a] 45 DAP	7 July,[a] 55 DAP	17 July,[a] 65 DAP	1 Aug.,[a] 80 DAP	20 Aug.,[a] 99 DAP	6 Sept.,[a] 116 DAP	21 Sept.,[a] 131 DAP
Crimson clover	V3	29.0	19.0	24.5	19.9	23.0	20.8	12.2	27.7
	V5	28.7	19.3	24.9	20.1	23.1	20.8	12.2	27.7
Radish	V3	29.1	18.9	24.4	19.9	23.0	20.8	12.1	27.7
	V5	28.8	19.2	24.9	20.1	23.1	20.8	12.2	27.6
Ryegrass	V3	29.1	18.9	24.5	19.7	22.9	20.7	12.1	27.3
	V5	29.9	19.3	24.7	20.2	23.1	20.8	12.2	27.6
No cover control		28.3	19.2	25.0	20.2	23.2	20.9	12.2	27.5

[a]No significant differences of means within each date reported from ANOVA using $\alpha = .05$.

TABLE 11 Means of remotely sensed canopy temperature at KBS B-1 (2017) compared between cover crop species and interseed timing from each image date. Days after planting (DAP) of maize is noted within each column

Cover crop species	Interseed timing	29 May,[a] 31 DAP	16 June,[a] 49 DAP	28 June,[a] 61 DAP	6 July,[a] 70 DAP	18 July,[a] 82 DAP	31 July,[a] 95 DAP	20 Aug.,[a] 115 DAP	6 Sept.,[a] 132 DAP	20 Sept.,[a] 145 DAP
Crimson clover	V3	13.9	25.6	17.2	28.6	17.6	23.6	23.1	11.5	22.9
Crimson clover	V6	14.1	26.0	17.0	28.7	17.9	24.0	23.2	11.5	22.9
Mixture	V3	14.0	25.7	17.0	28.4	17.4	23.8	23.3	10.8	22.8
None	None	13.9	25.9	17.3	29.3	18.1	23.8	23.3	11.2	22.9
Radish	V3	14.0	25.5	17.1	28.4	17.2	23.6	23.2	11.1	22.8
Radish	V6	13.9	26.0	17.3	29.2	16.4	23.9	23.2	11.3	22.9
Royal ryegrass	V6	14.0	26.0	17.2	29.2	15.6	24.0	23.3	11.0	22.9
Ryegrass	V3	14.0	25.5	17.1	28.7	17.2	23.6	23.3	11.5	22.9
Ryegrass	V6	14.0	26.0	17.1	28.9	18.1	24.0	23.3	10.8	22.9

[a]No significant differences of means within each date reported from ANOVA using $\alpha = .05$.

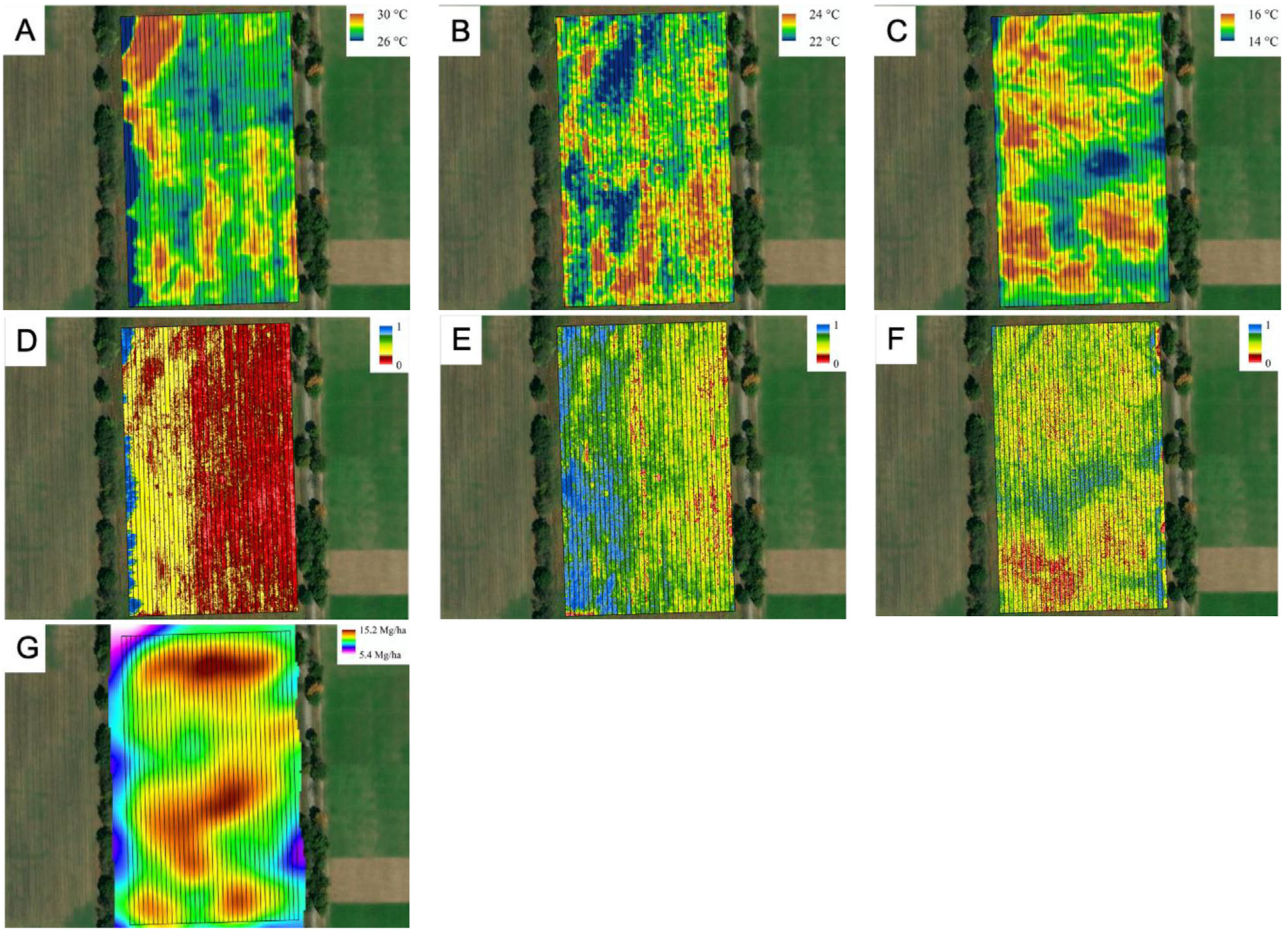

FIGURE 5 Thermal imagery (AirScout, Inc.) at KBS 30-2 in 2017. (a) Thermal image on 16 June, (b) thermal image on 28 June, (c) thermal image on 6 Sept., (d) advanced difference vegetation index on 16 June, (e) advanced difference vegetation index on 28 June, (f) advanced difference vegetation index on 6 Sept., (g) final yield map

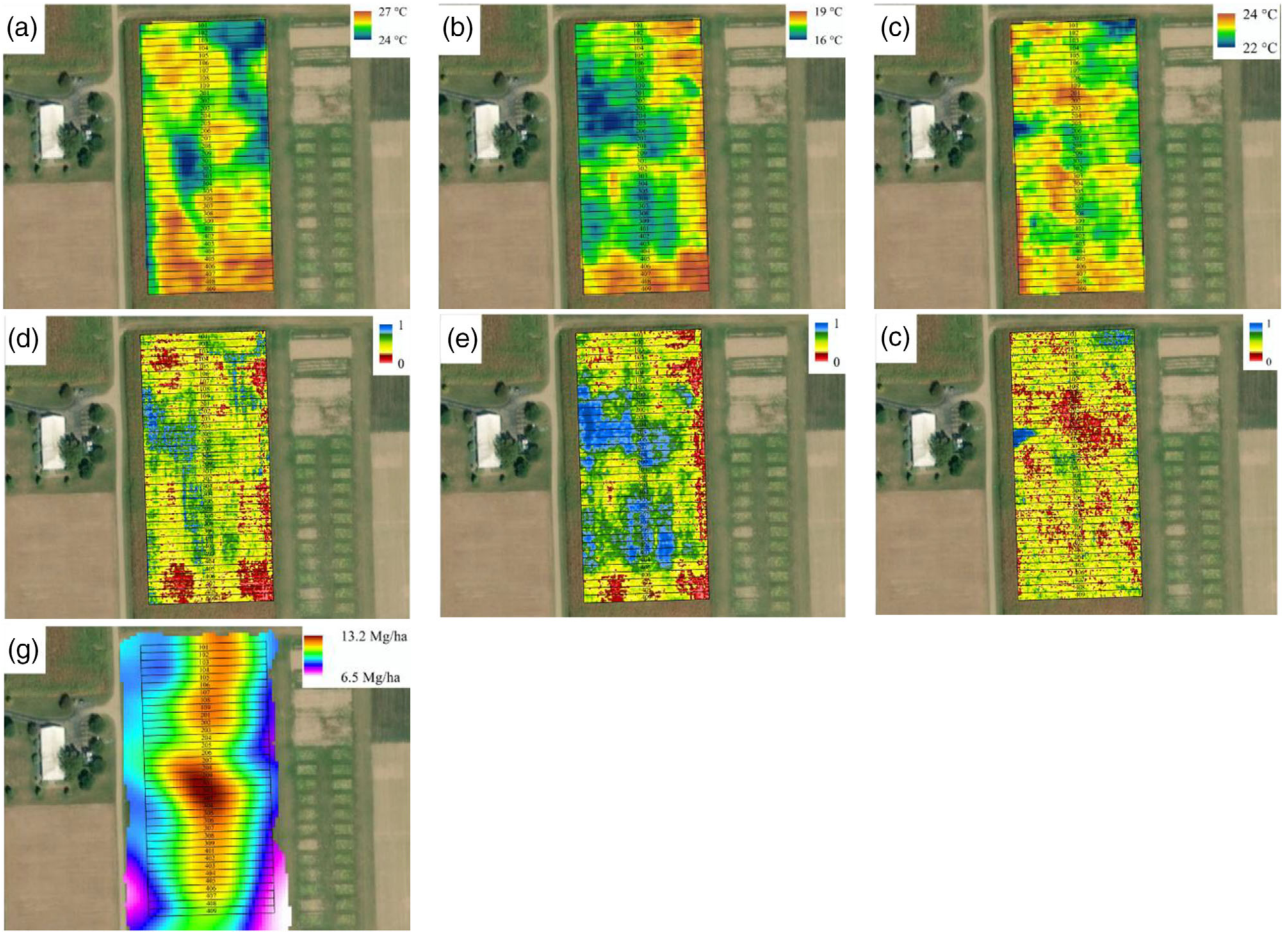

FIGURE 6 Remotely sensed imagery (AirScout, Inc.) at KBS B-1 in 2017. (a) Thermal image on 16 June, (b) thermal image on 28 June, (c) thermal image on 6 Sept., (d) advanced difference vegetation index on 16 June, (e) advanced difference vegetation index on 28 June, (f) advanced difference vegetation index on 6 Sept., (g) final yield map

purpose of this analysis. The climatological period varied based on the plentitude and availability from each site but ranged from 1997 and 2009 to the present. The list of sites used include: Hancock Turfgrass Research Center in East Lansing; Kellogg Biological Station in Hickory Corners; and Saginaw Valley Research and Extension Center in Richville, Albion, and Hart.

3 | RESULTS

3.1 | Small-trial research and on-farm trial research fields

3.1.1 | Interseeded cover crop effects on canopy reflectance of temperature

Results of the canopy reflectance's temperature show that there were no statistical differences between cover crop treatments, but as expected temperatures differed across sampling dates at MSUAF (Table 4). The subtle differences of reflectance variations shown on 16 June, 27 June, and 20 August are a result of inherent spatial variability of the field where the experimental plots were established (Figure 3a–c). At the SVREC site, canopy reflectance was not significantly different across cover crop species or interseed timing (Table 5). Thermal imagery from 17 June revealed patterns of higher temperatures in almost the complete first replicate of the trial design (Figure 4a) due to the dominance of soil exposure and low canopy cover present in this image. Plants reflected less heat as noted in the 8 July (Figure 3b) image.

3.1.2 | Interseeded cover crop effects on NDVI and NDRE

Tables 5 and 6 show the results of NDVI across sites and years. For MSUAF, NDVI was higher in plots where cover crops were interseeded at the V3 timing compared with the V6 interseed timing. The NDVI values found on 12 June are due the lack of biomass present within the plots allowing for a majority of soil to reflect an abundance of

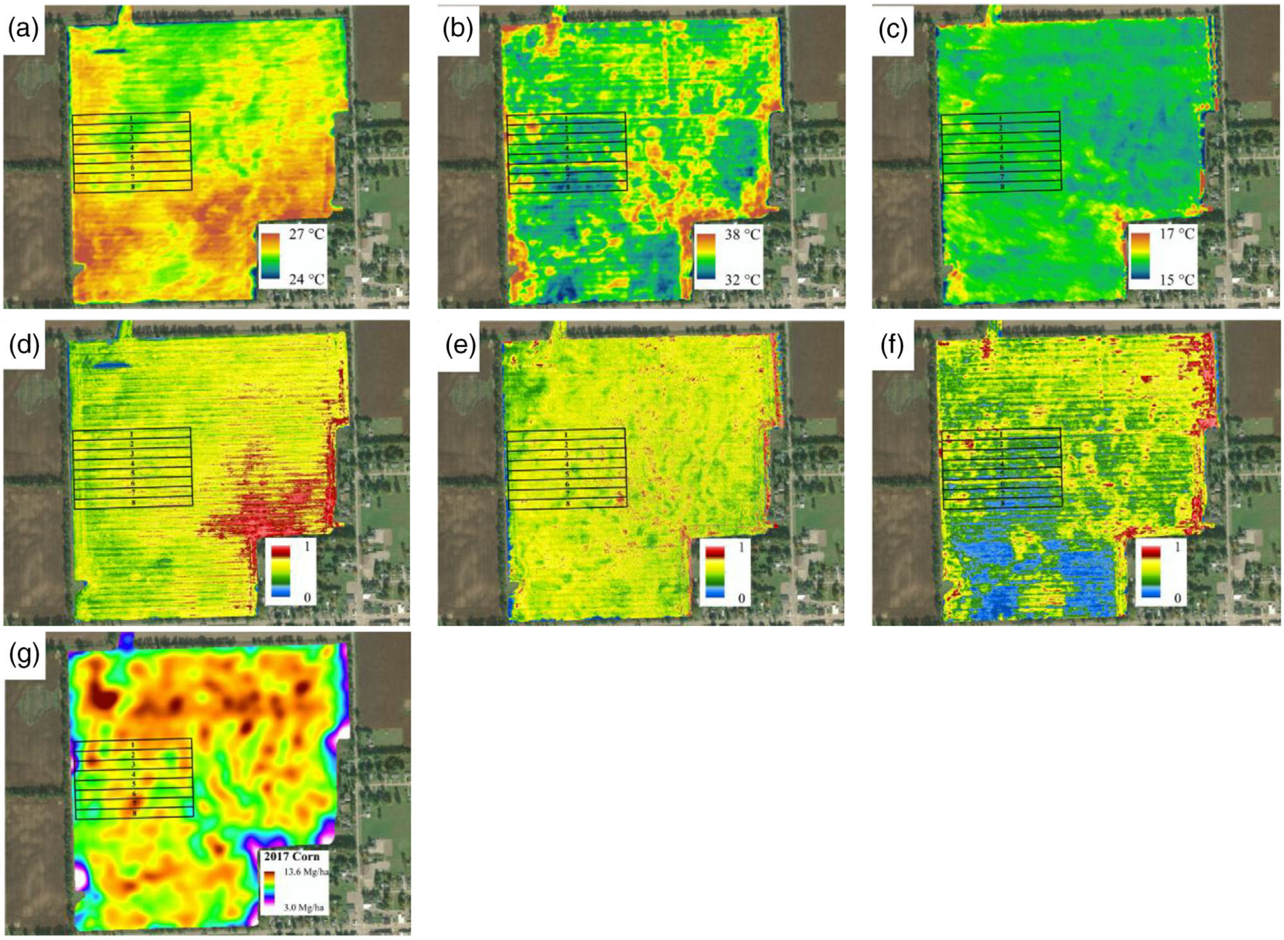

FIGURE 7 Thermal imagery (AirScout, Inc.) of Springport field in 2017. (a) Thermal image on 15 June, (b) thermal image on 6 July, (c) thermal image on 5 Sept., (d) vegetation index on 15 June, (e) advanced difference vegetation index on 6 July, (f) advanced difference vegetation index on 5 Sept., and (g) final yield map

infrared light. The images collected around 27 June (Figure 3b) and 30 June (Figure 3e, 3h) show slight patterns of lower plant reflectance in three distinct strips across the field in the thermal and NDVI imagery. The randomized experimental design of this trial therefore should prevent these variations as being interpreted as real treatment effects. A trend of consistent values relative to the timing of maize growth at each image date reflects the positive overall maize growth, regardless of the interseed treatments.

3.2 | Maize grain yield

At the MSUAF site, grain yield of the weedy plots averaged 7,393 kg ha^{-1}, while yields of all other plots ranged from 10,056 to 10,818 kg ha^{-1} (Table 7). At SVREC, weed biomass was negligible in all plots, and no differences in yield were observed comparing treatments (Table 7). Maize yields ranged from 11,181 to 11,808 kg ha^{-1}. Across all sites, maize yield in cover crop treatments did not differ from yield in the weed-free control. In Springport and Hart for all site years, there were no maize yield differences within cover crop species or interseed timing (Tables 8-10,11).

3.3 | Strip-trial research fields and field-scale on-farm trials

3.3.1 | Canopy temperature and maize grain yield

Imagery from the strip trials at KBS (Figures 5 and 6) reveal distinct patterns of higher and lower temperatures. There were no significant differences among temperatures across treatments at the nine image dates for both fields at KBS (Tables 6 and 7, 11.) Maize grain yield measurements taken from the combine's yield monitor showed no differences in yield of strips with interseeded cover crops compared with the untreated control strips (Table 7). Consistent with the trends observed from the small plot trials, actively growing cover

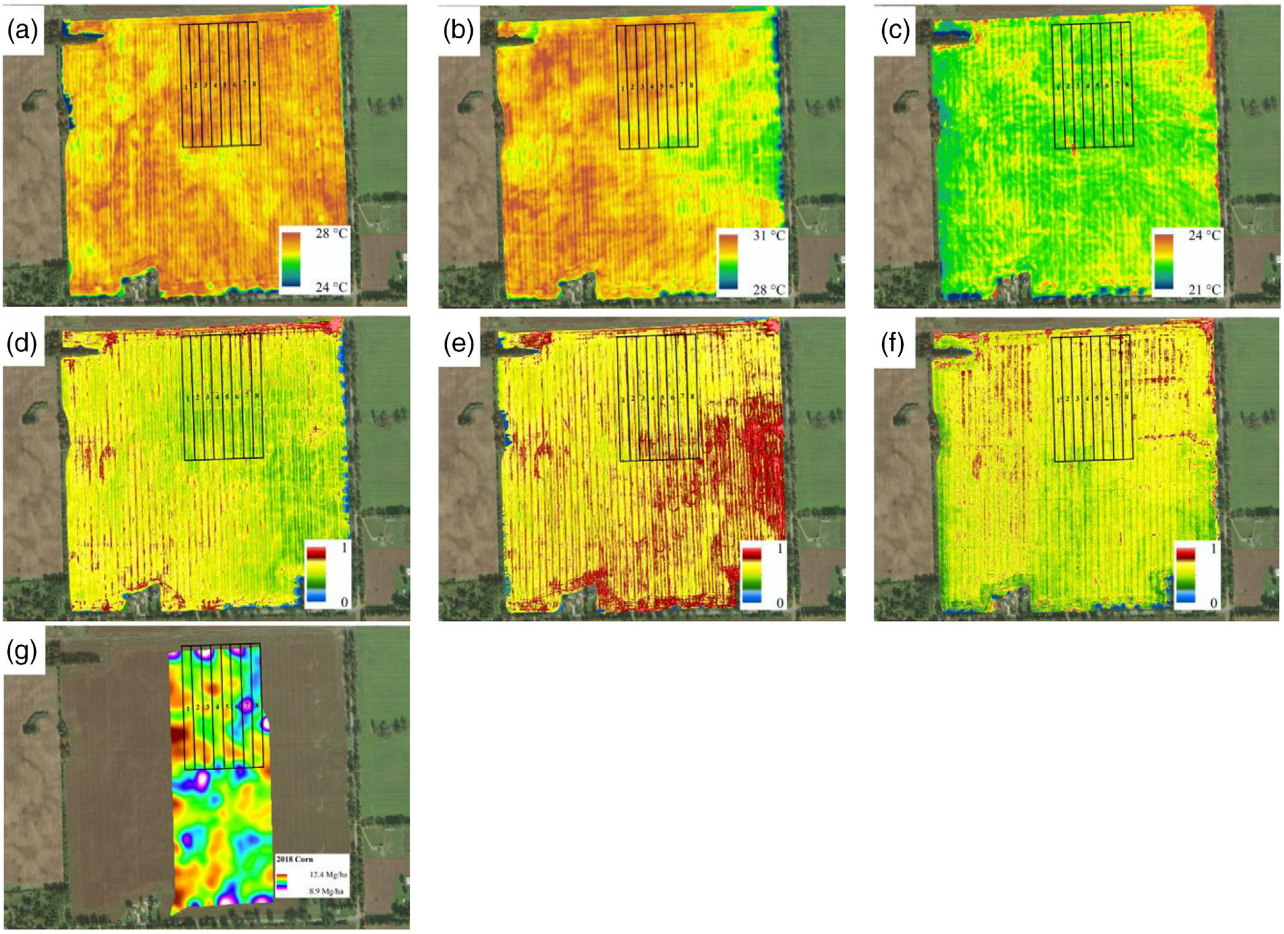

FIGURE 8 Thermal imagery (AirScout, Inc.) of Springport field in 2018. (a) Thermal image on 6 June, (b) thermal image on 18 June, (c) thermal image on 14 Sept., (d) advanced difference vegetation index on 6 June, (e) advanced difference vegetation index on 18 June, (f) advanced difference vegetation index on 14 Sept., and (g) final yield map

crops did not negatively impact grain yields. In Springport for all site-years, there were no maize yield differences within cover crop species or interseed timing (Tables 8 and 9).

4 | DISCUSSION

This is the only research, as far as we are aware, that evaluated the impact of cover crop species and mixtures, interseeding date, and scales (small-trial vs. strip-trial vs. field-scale) on in-season maize growth and yield using remote sensing imagery analysis incorporating different remotely sensed sensors (visible bands, NIR, and thermal from different platforms and resolutions). The canopy temperature measured with the thermal camera is a result of the plant's response to air temperature, soil temperature, and available water prior to the measurement. Soil temperature is higher than the plants' temperatures, and the plants' canopy may reflect less heat when more soil is exposed as noted in the 8 July (Figure 4b) image. This pattern is almost uniform among all the treatment blocks. Since canopy temperature is strongly influenced by air temperature, soil temperature, canopy closure, and evapotranspiration (Sauer, Singer, Prueger, DeSutter, & Hatfield, 2007), our results confirmed the effects of these interactions on plant canopy temperature. At the SVREC site, canopy temperatures were usually higher early in the season compared with later in the season due to the full canopy cooling off due to the transpiration process. Since there was <10 mm of rainfall from late May to mid-July, temperatures were likely influenced by differences in soil available water to plant, which affected canopy temperature: as the canopy closes, less bare soil exposure lowered canopy temperatures, in addition to transpiration (Figure 2). The differences in the weed-free plots in July at the SVREC location were likely due to bare soil under the maize canopy compared with plots interseeded with cover crops. The higher NDVI observed where cover crops were interseeded at the V3 timing compared with the V6 interseed timing occurred only for the 21 June image; no significant differences in NDVI occurred when measurements were taken after the V6 growth stage (data not shown).

The observed increases in NDVI as the season progressed were driven by maize growth and increased canopy closure.

Overall, it appears that cover crops contribute only slightly to increased NDVI as increased cover crop biomass did not correlate to higher NDVI; secondly, remote sensing did not always detect differences in NDVI when cover crops were interseeded. At MSUAF, NDVI was greater in V3 plots compared with V6; however, this measurement was on 26 June, prior to the V6 interseeding. Following the V6 interseeding, no differences in NDVI were observed.

Remote sensing of canopy temperature was used as a method to detect if the competition of the cover crop with the maize would negatively impact the grain yield. Cover crops did not alter canopy temperature compared with the no cover crop control plots at KBS, Springport, and Hart. The spatial variability of maize yield was a considerable factor, as clearly shown in the images (Figure 5). At field 30-2, the final yield map (Figure 5g) does not show any relationship with the previous remotely sensed imagery (Figure 5a–f). Previous studies have shown that remote sensing using NDVI only predicts about 40% of the variability of maize yields (Maestrini & Basso, 2018). No significant differences were recorded among temperatures across treatments at the nine image dates for both fields at KBS (Tables 4 and 11.) Consistent with the trends observed from the small plot trials, actively growing cover crops did not negatively impact grain yields.

The field-scale on-farm trials at Springport and Hart added large blocks of randomized cover crops to their fields by using precision agriculture technologies. Imagery captured from these fields each year showed the same behavior; inherent field-scale variability was greater than any treatment effect from the interseeded cover crops (Figures 7 and 8).

Remote sensing was unable to detect cover crop presence in maize prior to canopy closure as evidenced by the lack of significant differences in NDVI and NDRE in the interseeded treatments compared with the weed-free control at the small plot trials of MSUAF and SVREC (Tables 5 and 6). Remote sensing is a valuable tool for farmers to visualize the spatial patterns of variability of their crops during the critical stages of cover crop establishment, especially when their fields include varying soil types and topography. This study highlights that cover crops can be interseeded with maize without impacting maize grain yield in Michigan. The inherent field-scale variability was greater than any treatment effects and needs to be considered to account for dynamic interactions between the plant, soil, field, topography, and management practices. Cover crops in our research did not contribute to differences in canopy temperature, an important indicator of crop stress. We were interested in determining if cover crops influenced canopy temperature during maize pollination or grain-fill. Water stress during these times can result in reduced maize grain yield (Cakir, 2004; Otegui, Andrade, & Suero, 1995). Additionally, cover crops could compete with maize for nutrients during pollination and grain fill, two times during the growing season where nitrogen demand increases (Ciampitti & Vyn, 2013). There were no differences in maize yield in the no cover control compared with yield where various cover crop species were seeded at the V3 or V6 growth stages, regardless of seeding rate. We conclude that cover crops in this system did not compete with maize and no differences were detected between cover crop treatments (timing and species) from remotely sensed thermal and optical reflectance. Inherent spatial variability was the predominant factors in image variations, as no differences were found among treatments at this scale.

Cover crop biomass was collected and reported in Brooker, Renner, and Basso (2020) at the Small-Trial Research Fields and in Brooker, Renner, and Sprague. (2020) at the On-Farm Field Research Trials. The cover crop biomass measurements were not taken simultaneously with every remotely sensed image, yet the images confirm that the presence of actively growing cover crops did not inhibit maize growth in a way that was identified through vegetation indices or final maize yield collected at harvest.

5 | CONCLUSION

This study focused on remotely sensed imagery and its ability to discern plant health concerning the introduction of an interseeded cover crop. We evaluated if interseeding cover crops into maize crops across different spatial scales showed spectral and thermal differences in the image analysis. No significant differences in optical reflectance (visible, NIR, and RedEdge), and canopy temperatures were found among treatments. Cover crops did not enhance or reduce maize grain yield compared to the no cover control treatment. Our results indicate that differences in maize growth at field scale were due to inherent variability, and not from the cover crops interseeded in maize.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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