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Equipment Development to Manage Cover Crops for Small and Urban No-till Farming Systems

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In recent years, cover crop use in no-till organic production systems has steadily increased. Unincorporated cover crop residue forms a mulch layer on the soil surface that protects against erosion, runoff, soil compaction, and weed pressure, while conserving soil water. These covers must be managed and terminated appropriately to prevent planting problems. Field experiments (2014 and 2015) evaluated two equipment prototypes at 1.0 and 2.2 km/h to terminate cereal rye and crimson clover (legume) cover crops in small conservation farm settings; both were walk behind tractor devices. The first was a PTO driven powered roller/crimper (roller), and the second used heat from engine exhaust via a steel tube (477 K) and from electric heat strips (733 K) powered by an on-board generator to flatten and terminate cover crops. Treatments applied to mature cover crops were: exhaust heat (with or without supplemental heat strips); exhaust heat (with or without supplemental heat strips) combined with the roller; and roller only. Termination data and volumetric soil moisture content (VMC) were collected weekly for three weeks after termination.
Results were compared to untreated cover crops (control). During the two year experiment, average rye termination rates were significantly higher (93 to 97%) for the combination of exhaust heat with supplemental heat strips and the roller at both speeds compared to engine exhaust heat only, exhaust heat with heat strips, and the roller alone (87 to 92%). Standing (untreated) rye had a termination rate of 59%. Similarly, the higher average termination rates for crimson clover were observed for the combination of roller and exhaust heat with supplemental heat strips at two speeds (70 to 74%) compared to exhaust with supplemental heat strips only at two speeds (66 to 69%). The control for crimson clover was 33%. Plots with flattened cereal rye residue had higher VMC than the control in 2014 (all 3 weeks of evaluation) and in 2015 (first week of evaluation only), indicating better soil water conservation. For crimson clover (except for two weeks after rolling in 2015), no difference in VMC between flattened residue and untreated (standing clover) was observed possibly due to denser soil coverage by standing clover compared to greater spacing between stems of standing cereal rye. Overall, findings from this two years field study indicate that combining the roller/crimper and exhaust heat with supplemental heat strips is a viable alternative for organic production systems where effective cover crop termination (without commercial herbicides) is essential for cash crop growth and optimal yields.

1. Introduction

The expansion of fresh food production by local small vegetable farms relies on sustainable practices that include no-till systems using cover crops. Cover crops provide important benefits such as reducing runoff and soil erosion, reducing soil compaction and weed pressure through mulching and allelopathy, while conserving soil water and adding organic carbon (C) to soil (Reeves, 1994). In addition to soil C contributions, legumes also produce nitrogen (N) as a natural source of N-fertilizer that is important in organic production systems (Hubbell and Sartin, 1980). In the Southern United States, the recommended time to plant cash crops into residue cover is typically three weeks after cover crop was terminated at the appropriate growth stage and when the termination rate exceeds 90% (Ashford and Reeves, 2003); this minimizes resource competition between cover and cash crops. Thus, proper management of cover crop residues is the key to achieve effective no-till planting of cash crops into residue cover without interfering with planting operations (Kornecki et al., 2006). There are different cover crops management methods. One is mechanical termination utilizing

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rolling/crimping technology. This requires injuring plants with crimping bars without cutting stems. Another method is to injure (desiccate) plants using a heat source. Heat can damage the structure of proteins in plant tissue. According to Levitt (1980), heat begins to damage plant cells at ~40°C, and as temperature increases linearly, the heat-killing time decreases exponentially. In another investigation, Ascard (1997) stated that the critical temperature for effective leaf mortality ranges from 55°C to 70°C with an exposure time of 65 to 130 milliseconds. However, since a temperature gradient is required to drive heat into plants, a greater minimum temperature is also required. The mechanism of plant injury due to heat is associated with loss of membrane semi-permeability and cuticle breakdown causing plant desiccation and chemical decomposition.

One readily available source of free heat energy for injuring plant tissue (and possibly used for cover crop termination) is exhaust heat from internal combustion engines. On average, the efficiency of a diesel or gasoline engine is only 30%. Analyses performed by Jadhao and Thombare (2013) demonstrated that energy from burning fuel in an internal combustion engine produces heat which is exchanged with the engine’s cooling system, and 30% of this heat is lost to the environment via the exhaust system (manifold, pipes, and muffler). In the automotive industry, some engine designs utilize exhaust gases to power a compressor to supply more air to the intake manifold for increased engine efficiency and power (i.e.: turbocharger). However, this technology is not used in all engines, therefore exhaust manifold heat is often wasted. Heat has been used in agriculture in the form of an open flame system or steam to control weeds by damaging plant tissue (Collins, 1999). However, these systems require an additional fuel source and according to Knezevic and Ulloa (2007), 42 to 50 kg/ha of propane can achieve 80% weed termination. In contrast, Kornecki et al. (2014) focused on utilizing wasted exhaust heat to terminate cover crops and control weeds in conservation systems.

To determine the effectiveness of this concept, a BCS two-wheel walk behind tractor (one cylinder Honda gasoline engine) was used. The exhaust system was modified by attaching an insulated pipe that transferred exhaust heat to a rectangular perforated steel tube that was in direct contact with the flattened cover crop.

The objective of this field study was to evaluate two different experimental techniques for terminating cereal rye and crimson clover cover crops for a small, organic farm conservation agriculture setting.

2. Experimental procedure

A field experiment was conducted in the 2014 and 2015 growing seasons. The experiment was a randomized complete block design with three replications. Two different experimental devices developed at the National Soil Dynamics Laboratory in Auburn, AL USA were used in the experiment. The first device was a 0.91 m wide patented powered roller/crimper for a walk behind tractor (Figure 1A; Kornecki, 2012) and the second was a 0.8 m wide heat pusher (Figure 1B, Kornecki et al., 2014). For the heat pusher, the exhaust heat generated by the single cylinder Honda 9.7 kW gasoline engine (powers an Italian made BCS-853 walk-behind tractor) is channelled from the exhaust manifold to an insulated delivery pipe and then to a Y-shaped insulated divider (Figure 1B) that delivers and equally distributes the exhaust heat to a rectangular steel tube (shown in Figure 2A) that is in continuous contact with the cover crop. To assess the cover crops termination rates, a handheld, chlorophyll meter SPAD 502 light sensor-based from Konica-Minolta (Ramsey, NJ, USA) was used to measure the chlorophyll activity “greenness” of covers. The SPAD data were converted to calculate termination rates using a linear regression equation and procedure described by Kornecki et al. (2012).

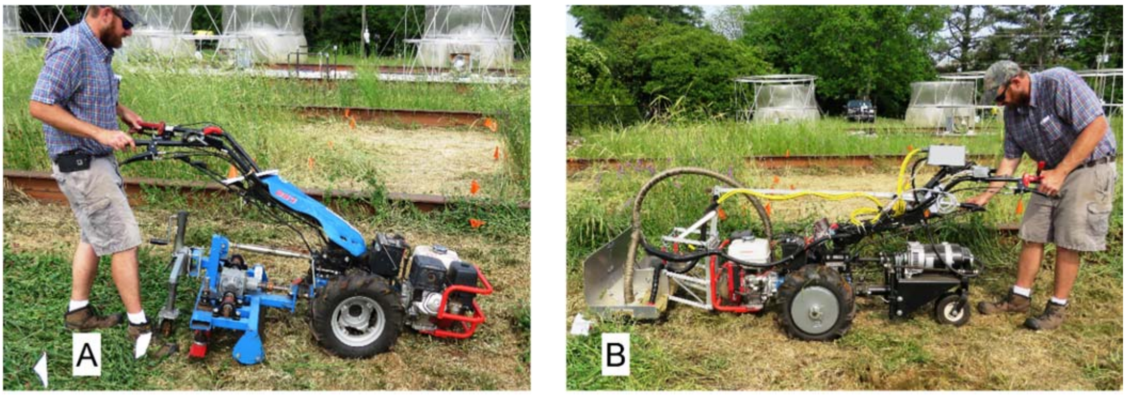

Figure 1. Tested devices: A) powered experimental roller/crimper (Kornecki, 2012, US patent # 7,987,917 B1); and B) heat exhaust–strip cover crop pusher (Kornecki et al, 2014, patent pending No. 14/501,424).

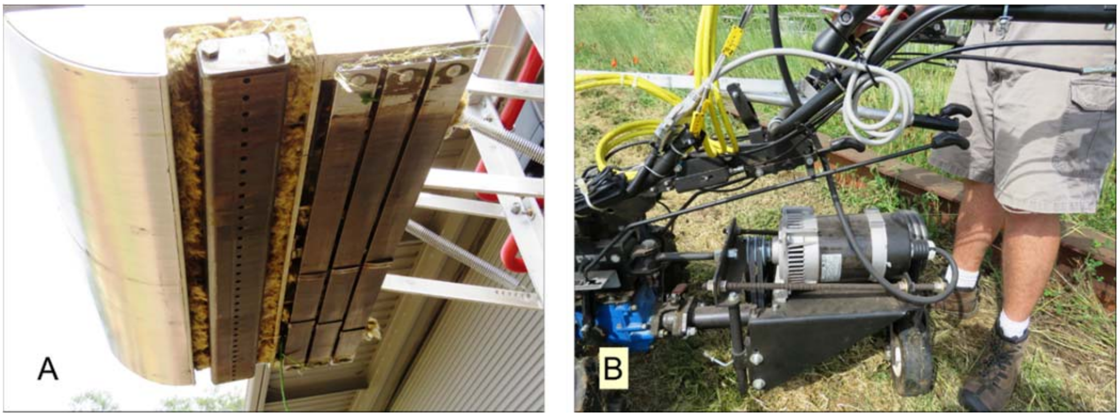

Figure 2. Heat pusher components: A) exhaust rectangular steel tube with three supplemental heat strips; and B) heat strip power source is a 240 V on board AC generator powered by the PTO.

The steel tube was perforated at the bottom so that hot exhaust gases was released to injure the cover crop. In addition to utilizing exhaust heat, a PTO powered 6.0 kW generator installed on the tractor produced electricity (Figure 2B) that energized three 3.81 cm wide 240 V AC, 0.75 kW strip heaters (Figure 2A) that causes further plant tissue injury. Both the heated steel tube and heat strips were in direct contact with the cover crop. Heat strips were individually controlled by a programmable temperature controller with proportional-integral-derivative software. Data were collected with a Measurement Computing USB-5201, 8-channel thermocouple input temperature logger at 1 Hz rate. The bottom of each strip heater was equipped with a type K-thermocouple to precisely record temperature. The supply pipe from the engine exhaust (147.3 cm long) was split with a Y-connector (2 pipes 45.7 cm long) to divert exhaust to two entry points 12.7 cm from each end of the heated pipe (Figure 1B). Speeds of 1.0 km/h and 2.2 km/h were used in testing the efficiency of the heat system.
Termination data were collected one, two, and three weeks after cover crop rolling and compared with untreated cover crop plots. Rye was terminated at the early milk growth stage and crimson clover at full bloom growth. During weekly evaluations (for 3 weeks), soil VMC was also measured with a portable TDR meter (Spectrum Technologies, Aurora, IL, USA) to determine soil water conservation due to treatments. Data were subjected to analysis of variance and treatment means were separated using the ANOVA GLM procedure; the Fisher's protected Least Significant Differences (LSD) test at the 10 % probability level was used (SAS, 2009).

Table 1. Treatment description and treatment abbreviations (same treatments for 1.0 and 2.2 km/h speeds).

Treatment	Treatment abbreviation (in tables)
Heat from exhaust only	EXH
Heat from exhaust + Strip heat	EXH+HS
Heat from exhaust + Strip heat + Power roller/crimper	EXH+HS+PRC
Heat from exhaust with Power roller/crimper	EXH+PRC
Power roller/crimper only	PRC
Untreated cover crop as a control (not rolled down)	Control

In 2014, the above treatments were applied on April 21 and May 5 for cereal rye and crimson clover, respectively. In 2015, treatments were applied on April 21 for cereal rye and April 22 for crimson clover.

3. Results and discussion

3.1 Heat distribution results

Thermocouple readings showed that the device generated 477 K (204^{o}C) and 733 K (460^{o}C) at the cover crop contact points for the heated steel pipe and each flat heater strip, respectively. The temperature measured at the exhaust manifold was 1088 K (815^{o}C). Efficiency of the exhaust heat applied to the cover crop was calculated using the following equation (1); where Q is the heat efficiency; Tc is the temperature (K) at the tube contacting the cover crop; and Th is the temperature (K) measured at the exhaust manifold.

$$Q = 1 - \frac{Tc}{Th} \quad (1)$$

Based on temperature data collected by the acquisition system, this equation calculates a 56% efficiency for heat transfer from the exhaust manifold to the delivery tube applying heat to the cover crop. System efficiency could be further increased by shortening the delivery points from the exhaust manifold to cover crop and utilizing better insulation materials to reduce heat exchange between the delivery pipe and the atmosphere.

3.2 Cover crop biomass and termination data

In 2014, dry biomass production for rye was 6723 kg/ha and 5869 kg/ha for clover; this was lower compared to 2015 ($P < 0.0001$) where rye produced 9036 kg/ha and clover generated 7085 kg/ha. Significant differences in termination results occurred among years, weeks of evaluation and treatments for both covers ($P < 0.0001$), thus data for each year, each of 3 weeks, and rolling treatments were analyzed separately for rye and clover.

3.3 Cereal Rye termination rates

One week after rolling in 2014, termination rates for rye were higher for the combination of exhaust heat, strip heat and the roller at two speeds (from 83.9% to 89.9%, Table 2); this was two times higher than the control (40.6%). A similar trend of higher termination was observed two weeks after rolling for treatments where the roller was added with exhaust and strip heat (88.0% to 94.8%) compared to 50.6% for the control. At three weeks after rolling, no differences in rye termination rates were observed among the rolling treatments (97.4% - 100%), but all were significantly higher than the control (89.8%). For one week after rolling at 1.0 km/h in 2015, no differences in termination rates (86.3% - 92%) among treatments were detected. At 2.2 km/h, a higher termination rate (89.9%) was found with the exhaust and heat strip with the roller, but no different than other treatments, except for exhaust with heat strip (83.1%). Termination rate for the control was 31.5%. At 2 weeks after termination, there were no treatment differences at both speeds; rates ranging from 96.8% to 100% were significantly higher than the control (60.8%). Similarly, at 3 weeks after termination there were no differences among speeds and treatments (100%) compared to the lower rate of 81.3% for the control.

Table 2. Termination rates (%) for Cereal Rye during the 2014 - 2015 growing seasons.

Treatment description		2014			2015		
		1 week	2 weeks	3 weeks	1 week	2 weeks	3 weeks
Speed 1.0 km/h	EXH	64.3 d*	81.0 bcd	100 a	86.3 abc*	99.6 ab	100 a
	EXH+HS	75.8 bc	81.2 bcd	97.4 a	91.1 a	100 a	100 a
	EXH+HS+PRC	89.9 a	94.8 a	99.8 a	90.5 a	100 a	100 a
	EXH+PRC	82.8 bc	89.6 ab	100 a	88.7 abc	100 a	100 a
	PRC	77.3 bc	84.6 abc	98.8 a	92.0 a	99.9 ab	100 a
Speed 2.2 km/h	EXH	69.5 cd	79.3 cd	100 a	88.8 abc	98.8 ab	100 a
	EXH+HS	63.9 d	72.5 d	99.5 a	83.1 c	100 a	100 a
	EXH+HS+PRC	83.9 ab	88.0 abc	100 a	89.9 ab	100 a	100 a
	EXH+PRC	74.6 bc	83.4 bc	100 a	83.5 bc	96.8 ab	100 a
	PRC	69.7 cd	82.2 bcd	99.3 a	87.6 abc	100 a	100 a
Control		40.6 e	50.6 e	89.8 b	31.5 d	60.8 c	81.3 b
P-value		<0.0001	<0.0001	0.0005	<0.0001	<0.0001	0.0005
LSD		9.6	10.3	4.4	6.8	3.3	1.7

*Same lower case letters in each column indicate no significant differences among treatments at $\alpha = 0.1$.

3.4 Crimson Clover termination rates

One week after rolling in 2014, there were no differences in termination among all treatments (Table 3), and these rates were higher (33.3% - 42.9%) than the control (4.2%). Two weeks after rolling, higher termination was obtained for the exhaust heat and roller combination, with or without heat strips (63.4 - 67.9%). The control was 26.1%. A similar trend continued 3 weeks after rolling where higher termination (90.3% - 90.8%) was observed for exhaust with strip heat and roller. The control had a termination of 46.2%. In 2015, clover termination was higher than in 2014. One week after rolling, higher termination rates were observed at 1.0 km/h for the combination of exhaust, supplemental strip heat and roller (72.5%). At 2.2 km/h, no differences in termination were found among treatments (54.1% - 58.3%), but they were higher than the control (12.2%). At 1.0 km/h, two weeks after rolling, a higher termination rate (88.8%) was found for the combination of exhaust, strip heat and the roller but not significantly different than exhaust heat alone and exhaust heat with the roller. At 2.2 km/h, higher termination (89.9%) was observed for exhaust heat with the roller but not different than exhaust alone and roller alone. At 1.0 km/h, 3 weeks after rolling, except for the exhaust with strips, other treatments produced higher termination (90.8% - 95.5%). At 2.2 km/h, the roller alone or adding the roller with exhaust or strip heat, produced higher termination rates (92.0% - 100%) than the exhaust heat with or without the strip heat (85.9% - 89.4%). Lower termination rate (75.1%) was for the untreated crimson clover control.

Table 3. Termination rates (%) for Crimson Clover during the 2014 - 2015 growing seasons.

Treatment description		2014			2015		
		1 week	2 weeks	3 weeks	1 week	2 weeks	3 weeks
Speed 1.0 km/h	EXH	42.0 a*	57.9 cd	82.9 bc	55.0 c*	83.3 bcde	93.1 ab
	EXH+HS	38.6 a	60.5 abcd	80.8 c	56.5 bc	77.7 e	85.8 c
	EXH+HS+PRC	36.8 a	66.3 ab	90.8 a	71.0 a	88.8 ab	92.1 ab
	EXH+PRC	41.1 a	66.6 ab	87.5 abc	62.9 b	84.3 abcd	95.5 a
	PRC	42.9 a	67.9 a	90.3 ab	60.1 bc	81.5 cde	90.8 abc
Speed 2.2 km/h	EXH	39.4 a	60.0 bcd	83.1 bc	57.4 bc	84.5 abcd	89.4 bc
	EXH+HS	33.3 a	53.4 d	85.0 abc	54.9 c	81.0 de	85.9 c
	EXH+HS+PRC	37.4 a	63.4 abc	90.3 ab	57.4 bc	78.8 de	92.0 ab
	EXH+PRC	38.7 a	65.2 abc	83.0 bc	58.3 bc	89.9 a	92.3 ab
	PRC	36.2 a	64.9 abc	88.7 ab	58.1 bc	87.7 abc	100 a
Control		4.2 b	26.1 e	46.2 d	12.2 d	36.3 f	75.1 d
P-value		0.0003	<0.0001	<0.0001	<0.0001	<0.0001	0.0005
LSD		10.5	7.9	7.6	6.4	6.6	5.7

*Same lower case letters in each column indicate no significant differences among treatments at α = 0.1.

3.5 Volumetric Soil Moisture content due to cereal rye

No differences were reported in the volumetric soil moisture content (VMC) between the two growing seasons for rye (P = 0.1995). However, rolling treatments had an effect on soil moisture (P = 0.0058). VMC results during three weeks of evaluation in each year are shown in Table 4.

Table 4. VMC (%) for cereal rye during the 2014 - 2015 growing seasons.

Treatment description		2014			2015		
		1 week	2 weeks	3 weeks	1 week	2 weeks	3 weeks
Speed 1.0 km/h	EXH	7.9 d	9.8 c	16.2 bc	12.8 bc	12.1	6.1
	EXH+HS	8.4 cd	10.1 bc	15.4 c	14.7 ab	13.4	8.2
	EXH+HS+PRC	9.5 abc	11.5 ab	17.1 ab	14.5 ab	13.6	6.7
	EXH+PRC	11.1 a	12.1 a	17.7 a	14.8 a	13.2	6.3
	PRC	10.5 ab	11.6 ab	17.2	14.4 ab	12.3	7.7
Speed 2.2 km/h	EXH	8.7 cd	11.1 abc	16.7 abc	14.6 ab	13.0	7.3
	EXH+HS	8.7 cd	11.9 a	17.5 ab	14.8 a	11.8	7.4
	EXH+HS+PRC	9.1 bcd	12.5 a	17.4 ab	16.0 a	13.2	9.1
	EXH+PRC	10.5 ab	11.6 ab	18.0 a	15.8 a	13.6	8.7
	PRC	8.5 cd	10.2 bc	16.1 bc	14.3 ab	12.2	6.4
Control		4.4 e	5.6 d	12.2 d	11.7 c	9.2	5.6
P-value		<0.0001	<0.0001	<0.0001	0.0483	0.1500	0.3533
LSD		1.6	1.6	1.5	6.4	N/A	N/A

*Same lower case letters in each column indicate no significant differences among treatments at α = 0.1.

In 2014, rolling treatments for cereal rye had higher soil moisture conservation one, two, and three weeks after termination (P < 0.0001) compared to the control (Table 4). At one week after rolling in 2015, rolled rye treatments had significantly higher VMC (12.8% to 15.8%) compared to standing rye (11.7%) indicating soil moisture conservation. In contrast, VMC for rolled rye 2 and 3 weeks after rolling was not statistically different than the control, but had numerically higher VMC. Rolled rye provided better soil coverage compared to more spaced standing rye (control) which reduced surface water loss due to a mulch effect.

3.6 Volumetric Soil Moisture content due to crimson clover

VMC for crimson clover was significantly different between years (P < 0.0001) and weeks (P < 0.0001). In 2014 during 3 weeks of evaluation and in 3-rd week after rolling in 2015, treatments had no effects on VMC with averages of 15.9%, 12.4% and 8.5% one, two, and three weeks in 2014 and 8.7% three weeks after rolling in 2015 (Table 5). It was likely due to denser soil coverage by untreated clover compared to more spaced stems of standing rye. At one and two weeks after rolling in 2015, there was a significant effect on moisture at one week, but this was unusually high (27.3% - 24.3%) for treated residue and 22.4% for untreated clover due to rainfall (36 mm). Two weeks after termination in 2015, higher VMC of rolled crimson clover (11.5 - 13.6%) compared to untreated clover (10.3%) indicated soil water conservation.

Table 5. VMC (%) for crimson clover during the 2014 - 2015 growing seasons.

Treatment description		2014			2015		
		1 week	2 weeks	3 weeks	1 week	2 weeks	3 weeks
Speed 1.0 km/h	EXH	15.4	13.0	8.3	25.0 bcd	12.9 ab	8.9
	EXH+HS	17.4	13.8	9.2	23.8 cde	11.2 cd	8.6
	EXH+HS+PRC	16.2	11.7	8.6	27.3 a	12.9 ab	9.2
	EXH+PRC	16.0	12.7	8.6	25.2 abcd	12.7 abc	9.4
	PRC	15.0	11.8	7.6	23.4 de	12.7 abc	8.9
Speed 2.2 km/h	EXH	17.3	13.0	8.8	25.7 abc	13.6 a	8.9
	EXH+HS	16.9	12.4	9.2	25.9 abc	13.0 ab	8.9
	EXH+HS+PRC	14.9	12.4	8.3	26.5 ab	12.1 abc	8.2
	EXH+PRC	14.9	11.7	7.9	24.4 bcde	11.6 bcd	8.6
	PRC	15.6	12.6	8.4	24.4 bcde	11.5 bcd	8.6
Control		14.8	11.5	7.9	22.4 e	10.3 d	7.9
P-value		0.7023	0.3650	0.1077	0.0387	0.0512	0.2930
LSD		N/A	N/A	N/A	2.2296	1.5443	N/A

*Same lower case letters in each column indicate no significant differences among treatments at α = 0.1.

4. Conclusions

Findings from two growing seasons indicated the heat system efficiency was 56% and could be improved by shortening and better insulating the pipe that delivers heat to cover crops. Combining the roller/crimper with exhaust heat and supplemental strip heat is a viable option for organic systems where commercial herbicides are not allowed and where effective cover crop termination is essential to cash crop growth. Flattened cereal rye had higher VMC than the control in 2014 (3 week evaluation) and only in the first week in 2015, indicating soil water conservation. Except for 2 weeks after rolling in 2015, no difference in VMC between rolled and standing crimson clover was found, possibly due to denser (than rye) soil coverage in untreated plots.

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