Weed Management, Reduced-tillage, and Soil Health:
Weed Ecology in Biodesign Farm's Organic, Minimum-Till Vegetable Production System

Organic Farming Research Foundation Grant 2007 Biodesign Farm, Stevensville, Montana 59870
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INTRODUCTION

Biodesign Farm was a small acreage, mixed vegetable crop, certified organic farm until sold in 2010. It began in 1993 using a living mulch system to manage weeds, build soil organic matter/cycle nutrients, and create habitat for natural enemies in annual vegetable production. Legumes (mostly clovers) were planted in between crop rows and maintained, with selective mowing, as an undisturbed cover crop during the growing season and winter. The following spring, legume row middles were tilled and became planting beds for the next growing season, while another legume living mulch was planted in between new crop rows. Manure/straw/clover compost was added to the entire field and incorporated every spring. Over a twelve year period, there were increases in soil nutrient levels and soil organic matter, abundance and diversity of natural enemies (esp. predators and parasites), and insect pest suppression. By 1998/2001, Biodesign had reduced/eliminated pest insect spraying.

Experiments to Futher Reduce Tillage. In 2005, vegetable production moved to a new field (previously 50 year-old pasture). The living mulch system was modified from spring-tillage/annual living mulch between crop rows to strip–tillage of crop rows only with no-till, perennial living mulch row middles. Fertilizer was reduced: compost or alfalfa meal was added each spring to strip-till crop rows only. In 2006, Biodesign investigated cabbage worm predation/parasitism by natural enemies found in both Brussels sprouts crop rows and the living mulch row middles between them. In 2007 Biodesign Farm implemented another on-farm experiment with Brussels sprouts to investigate how living mulch/weed competition and different in-crop-row tillage and weed management strategies affect both crop yield and long-term soil health measurements.

2007 WEED ECOLOGY EXPERIMENT ABSTRACT

Soil health and nutrient cycling, crop yield, and weed competition was evaluated in a perennial living mulch row middle system with different in-crop-row soil/weed management treatments: no-tillage, minimum-tillage, conventional tillage, tillage/sprayed with vinegar, and tillage/mulched with paper (Ecocover). None of the treatments received any fertilizer other than incorporated one-year-old red clover cover crop which was strip-tilled into crop rows in April. No-till red clover was maintained in row middles between strip-till experiment crop rows. RESULTS:

- **Perennial living mulch row middles did not reduce Brussels sprouts yield** as long as in-crop-row clover/weed competition was suppressed.
- **In-crop-row tillage and reduced vegetation cover increased crop yield**. The earliest and highest yield was recorded in tilled/paper mulch plots, followed by conventional tillage and tilled/vinegar-sprayed plots.
- **Yield was associated with soil temperature and vegetation cover**. Paper mulch and conventional-tillage plots had the highest soil temperatures from April through the end of August and the lowest vegetation cover (clover and weeds). Vinegar plots had cooler soil temperatures and more vegetation cover. Soil temperatures and yields were lowest and vegetation cover highest in no-tillage and minimum-tillage plots.
- **Associations between yield and soil nutrient levels were not clear**. Nitrate-nitrogen levels were highest early in the season in all treatments that had been tilled and lowest in no-tillage plots. However, by July and until the end of the growing season in September, the highest nitrogen levels were in both paper mulch and minimum-tillage plots, though these plots recorded the highest and next to lowest yields. In September, phosphorus (Bray 1) was highest in tillage/paper mulch plots and lowest in minimum-tillage, no-tillage, tillage, and tillage/vinegar plots.
- **Soil health measurements were generally highest in minimum-till and no-till plots and lowest in conventional tillage plots**. Arbuscular mycorrhizae and soil organic matter levels were highest in no-tillage and minimum-tillage plots and lowest in conventional tillage, tillage/vinegar plots, and paper tillage/mulch.
- **Tillage increased annual weed species abundance and diversity compared to no-tillage where perennial species were dominant**.

CONCLUSIONS AND CHANGES IN FARMING METHODS: Experiment results were used to further Biodesign's goal to combine long-term soil health/nutrient cycling, annual weed suppression, and improved predator/parasite habitat with economically acceptable yields. The farmer now utilizes no-till, perennial living mulches in between crop rows, spring in-crop-row minimum-tillage, and crop row mulches (mowed living mulch blown into or applied to crop rows pre/post-planting, depending on the crop).

EXPERIMENT DESIGN, TREATMENTS, and MEASUREMENTS

The design was completely randomized. Five treatments were replicated three times in an area that had been in red clover for one year. A total of 15 experimental plots were planted to Brussels sprouts (each 3 ft. by 50 ft.) within two contiguous 3-ft by 600-ft bed rows. A 10-ft border was left between each experimental plot within the rows. Four ft. wide no-tillage red clover row middles were left between the Brussels sprouts crop rows. Except for the no-till plots, all plots were mowed, chisel-plowed (one pass) with a single-shank plow, and tilled once (twice in conventional tillage plots) with 2 passes of a 3-ft tiller on 6 April. No supplemental fertilizer was applied. Brussels sprouts transplants were set on 7 May in double rows 24" apart with 24" between plants.

Treatments:

- **No-tillage:** flamed twice pre-plant in April and twice after planting in May using an infrared flame weeder (Eco-Weeder, purchased from Forevergreen)
- **Minimum-tillage:** tilled 6 April (see above for tillage details) and no further weed cultivation
- **Conventional Tillage:** Tilled on 6 April and again on 20 April and kept weed-free with three hoe cultivations (May, June, and July)
- **Tillage/Vinegar:** Tilled on 6 April and sprayed with 6.25% acetic acid vinegar once pre-plant (20 April) and twice after planting (May and June)
- **Tillage/Paper Mulch:** Tilled on 6 April and mulched with paper (Ecocover)

Left to right: 1) Ecocover paper mulch. 2) Conventional tillage plot after hoe cultivation. 3) July tillage/vinegar plot. 4) July minimum-tillage plot.

Measurements

- **Crop yield:** Four plants were harvested per treatment replicate on 3 weekly dates in September, for a total of 12 plants. Both individual sprouts and total plant biomass were measured.
- **Soil temperatures:** monitored twice monthly in all treatment plots.
- **Total percent cover**: evaluated twice monthly using a one 1-square-meter sample per plot.
- **Weed species composition**: evaluated twice monthly using a one 1-square-meter sample per plot.
- **Weed species encouraged by tillage**: evaluated twice monthly using a one 1-square-meter sample per plot in minimum-tillage plots and compared to an *untilled control of the original 50-year old pasture* and the *no-till, permanent clover living mulch between experiment crop rows*.
- **Weed species in on-farm-made compost**: evaluated twice monthly in nine 1 gallon pots of finished compost, which were kept in a greenhouse and watered until weeds germinated and grew to fill the pots.
- **Arbuscular mycorrhizae presence and soil aggregate stability** was performed by Dan Mummey, (microbiologist at the University of Montana, Missoula, MT). Five random samples were taken from three replicates for each of the five treatments on 7 September. Soil samples were kept cool until analyzed.
- **Percent organic matter and macronutrient content** was performed by A & L Western Agricultural Lab, Modesto, CA. Three random soil samples were taken monthly in each treatment April–September from 0-10 inches with a 3/4-inch-diameter, 10-inch-long soil probe.

Left to right: weed species and % cover measurements: 1) No-tillage (May). 2) Conventional-tillage (May). 3) Minimum-tillage (June).

RESULTS

Yield: Plants in tillage/paper mulch plots had more biomass and the highest average yield per plant (1.4 lb.), followed by conventional tillage (1.1 lb.) and tillage/vinegar plots (1.0 lb.). The lowest yield (0.41 lb.) and smallest plants were in no-tillage plots. Minimum-tillage yields (0.63 lb.) were higher than those in no-tillage plots, but lower than in conventional tillage, paper-mulch, and vinegar plots. Differences among all treatments (except conventional tillage and tillage/vinegar plots) were significant at $p < 0.05$).

Photos 1-3: harvest and yield measurements.

Soil temperatures: Paper mulch and conventional tillage plots had the highest soil temperatures from April through the end of August, followed by vinegar plots. Soil temperatures were lowest in the no-tillage and minimum-tillage plots all season (differences were significant at $p < 0.05$).

Total percent vegetation cover: Paper mulch and conventional tillage plots had the lowest vegetation cover (clover and weeds). Vinegar plots had more vegetation cover (50% by August). Vegetation cover was highest in no-tillage (100% by the end of June) and minimum-tillage (90% by the end of June) plots all season (differences were significant at $p < 0.05$). Clover began to move back into minimum-tillage plots within 3 weeks of tillage.

Weed species composition: By 17 June, the dominant vegetation species in all plots was red clover (*Trifolium pratense*) regrowth and seedlings. Red clover dominance is not surprising because the field had been planted to red clover for more than a year. During that time red clover was mowed periodically but it flowered and set seed in 2006. Only strip-tillage was done to prepare 2007 Brussels sprouts crop rows and row middles were maintained in no-till red clover living mulch. Some weed species were present in experiment plots in low numbers: Lamb's-quarter (*Cheonopodium berlandieri*), black medic (*Medicago lupulina*), wild buckwheat (*Polygonum convolvulus*), fanweed (*Thlaspi arvense*), white campion (*Silene alba*), and quackgrass (*Agropyron repens*) were recorded in all but the paper mulch plots.

Weed species encouraged by tillage and in on-farm-made compost greenhouse pots: More annual weed species, including some not found in crop fields or in the original un-tilled pasture, were recorded in the greenhouse-grown, one gallon compost pots, suggesting that some weed species may be brought in by compost ingredients, such as the off-farm sheep manure used in this on-farm-made manure/straw/red clover compost which was heated to NOP standards during the compost process (see Biodesign composting details). Comparing minimum-tillage experiment plots (where spring tillage was done, but no further weed cultivation occurred in 2007) to no-till clover row middles between experiment plot rows and also to a no-till pasture control area nearby, we found the highest number of annual weed species in the minimum-till plots; the untilled pasture control had the most perennial weeds and no annual weeds (Table 1).

Table 1. Weed Species and Lifecycle Differences					
Weed species	**Weed life cycle[1]**	**Un-tilled pasture**	**No-till living mulch**	**Minimum-till Plots**	**Compost pots**
Total annuals		**0**	**2**	**7**	**9**
Total biennials		**1**	**1**	**1**	**2**
Total perennials		**6**	**1**	**3**	**0**
Thlaspi arvense	A		X	X	X
Chenopodium berlandieri	A		X	X	X
Lactuca serriola	A			X	X
Portulaca oleracea	A			X	X
Sisymbrium altissimum	A				X
Echinochloa crus-galli	A				X
Malva neglecta	B	X	X	X	X
Hyoscyamus niger	B				X
Plantago lanceolata	P	X			
Plantago major	P			X	
Taraxacum officinale	P	X		X	
Silene alba	P	X	X	X	
Achillea millefolium	P	X			
Ranunculus acris	P	X			

[1]A = annual B = biennial P = perennial

Arbuscular mycorrhizae (AM) presence: The greatest AM density was observed in no-tillage plots; the second-greatest density occurred in minimum-tillage plots. The tillage/vinegar treatment resulted in the lowest AM density, followed by conventional tillage and tillage/paper mulch plots (Figure 1). Treatments with different letters are significantly different (p<0.05). Red clover is colonized by AM, but Brussels sprouts are not.

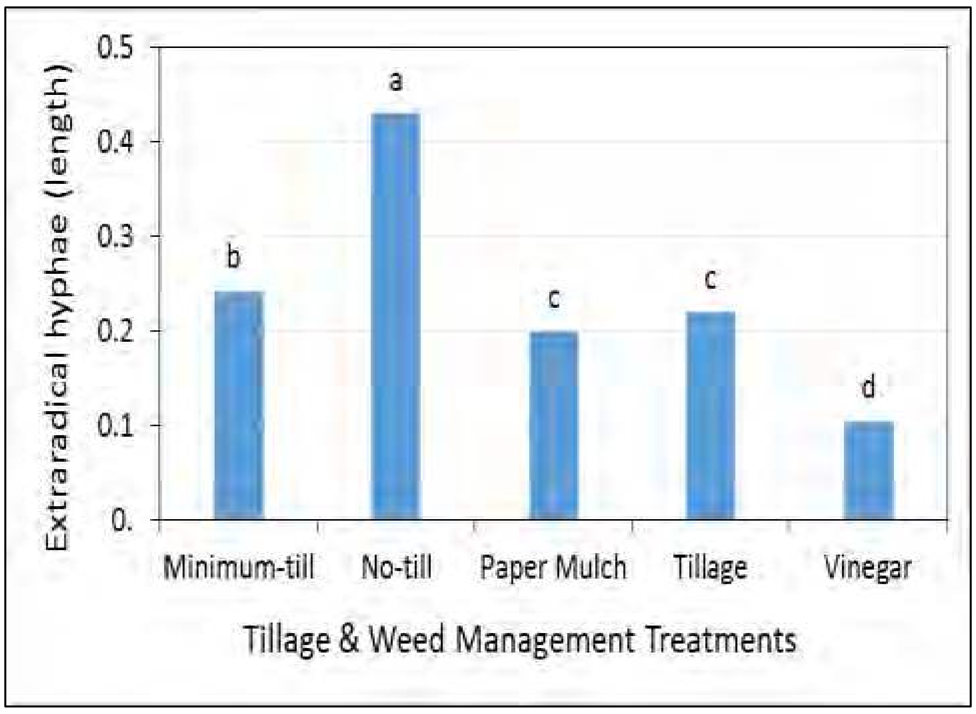

Figure 1. Arbuscular mycorrhizae (AM) density with 5 tillage and weed management treatments, 2007. Five random samples were taken from three replicates for each of five tillage treatments (no-till, minimum-till, tillage only, tillage + paper mulch, tillage + vinegar) on 7 September. Soil samples were kept cool until analyzed by Dan Mummey, microbiologist at the University of Montana, Missoula, MT. Extraradical hyphae lengths were measured as an indication of AM presence and density. Treatments with different letters are significantly different (p<0.05).

Soil Aggregate Stability

There were no statistically significant differences among treatments for soil aggregate stability.

Soil Organic Matter (SOM): SOM levels in April, one week after initial tillage was done (in all but the no-tillage treatments), were not statistically different. However, by 7 September, SOM levels were slightly higher in minimum-tillage and no-tillage plots. Treatments with different letters are significantly different (p<0.05) (Figure 2).

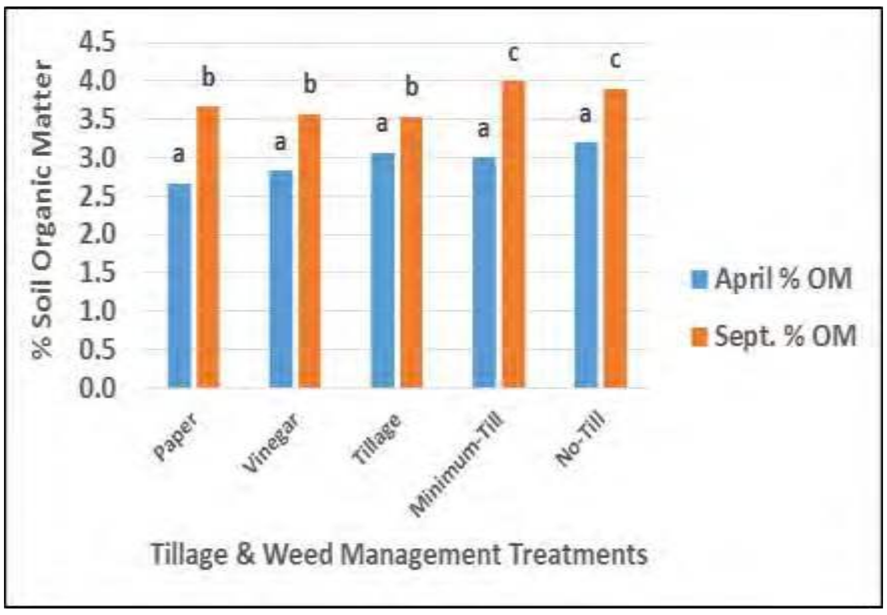

Figure 2. April and September soil organic matter levels in Brussels sprouts crop rows with 5 tillage and weed management treatments, 2007. Three random samples were taken in each treatment. All soil tests were taken from 0-10 inches with a 3/4-inch-diameter, 10-inch-long soil probe. Ten samples were taken, mixed in a bucket, and a two cup sample was sent for analysis. This was repeated for a total of 3 soil tests per treatment. Samples were analyzed by A & L Western Agricultural Lab, Modesto, CA. Treatments with different letters are significantly different (p<0.05).

Macronutrients:

Soil nitrate-nitrogen (N) in April, one week after initial tillage was done (in all but the no-tillage treatments), was highest in tillage/vinegar plots, followed by conventional tillage, tillage/paper mulch, and minimum-tillage treatments. N levels were lowest in no-tillage plots. At the end of the growing season on 7 September, N was highest in minimum-tillage and tillage/paper mulch plots and lowest in no-tillage, tillage, and tillage/vinegar plots. Treatments with different letters are significantly different ($p<0.05$) (Figure 3).

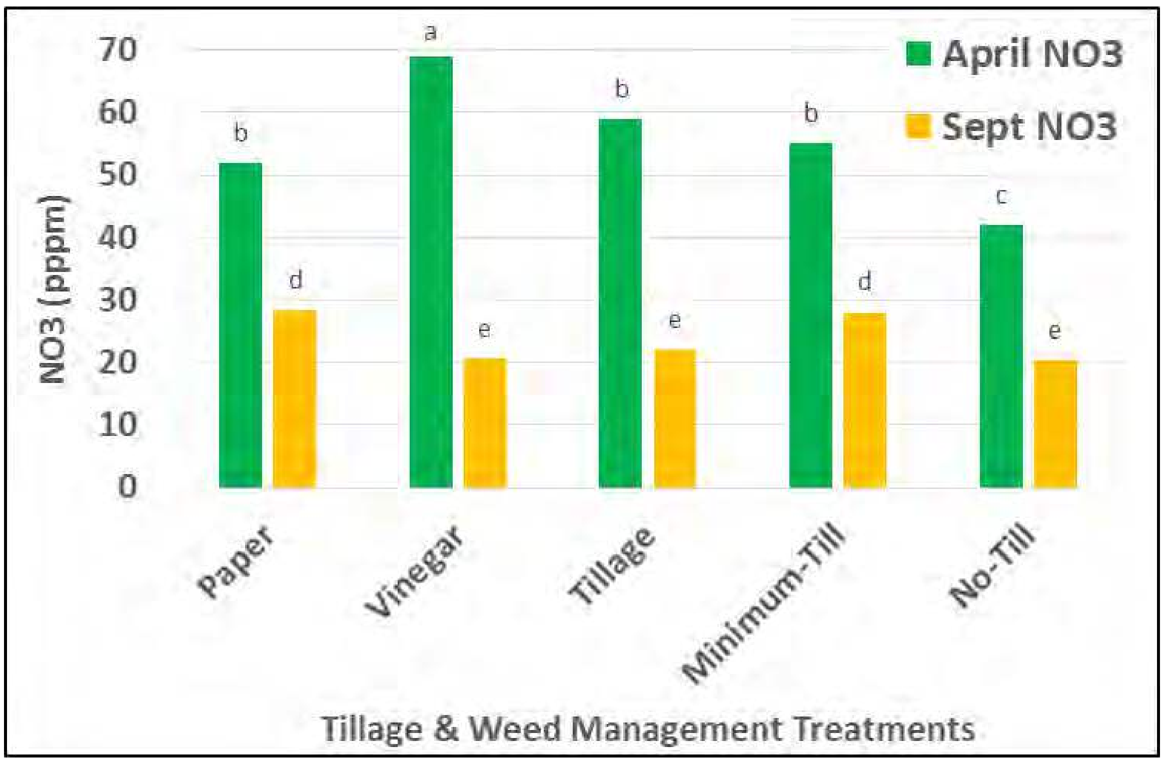

Figure 3. Nitrate-nitrogen (NO_3) levels in Brussels sprouts crop rows with 5 tillage and weed management treatments, 2007. Three random samples were taken in each treatment. All soil tests were taken from 0-10 inches with a 3/4-inch-diameter, 10-inch-long soil probe. Ten samples were taken, mixed in a bucket, and a two cup sample was sent for analysis. This was repeated for a total of 3 soil tests per treatment. Samples were analyzed by A & L Western Agricultural Lab, Modesto, CA. Treatments with different letters are significantly different ($p<0.05$).

Soil phosphorus, Bray P1, (P) levels in April, one week after initial tillage was done (in all but the no-tillage treatments), were not statistically different among treatments. In September, P was highest in tillage/paper mulch plots and lowest in minimum-tillage, no-tillage, conventional tillage, and tillage/vinegar plots. Treatments with different letters are significantly different ($p<0.05$) (Figure 4).

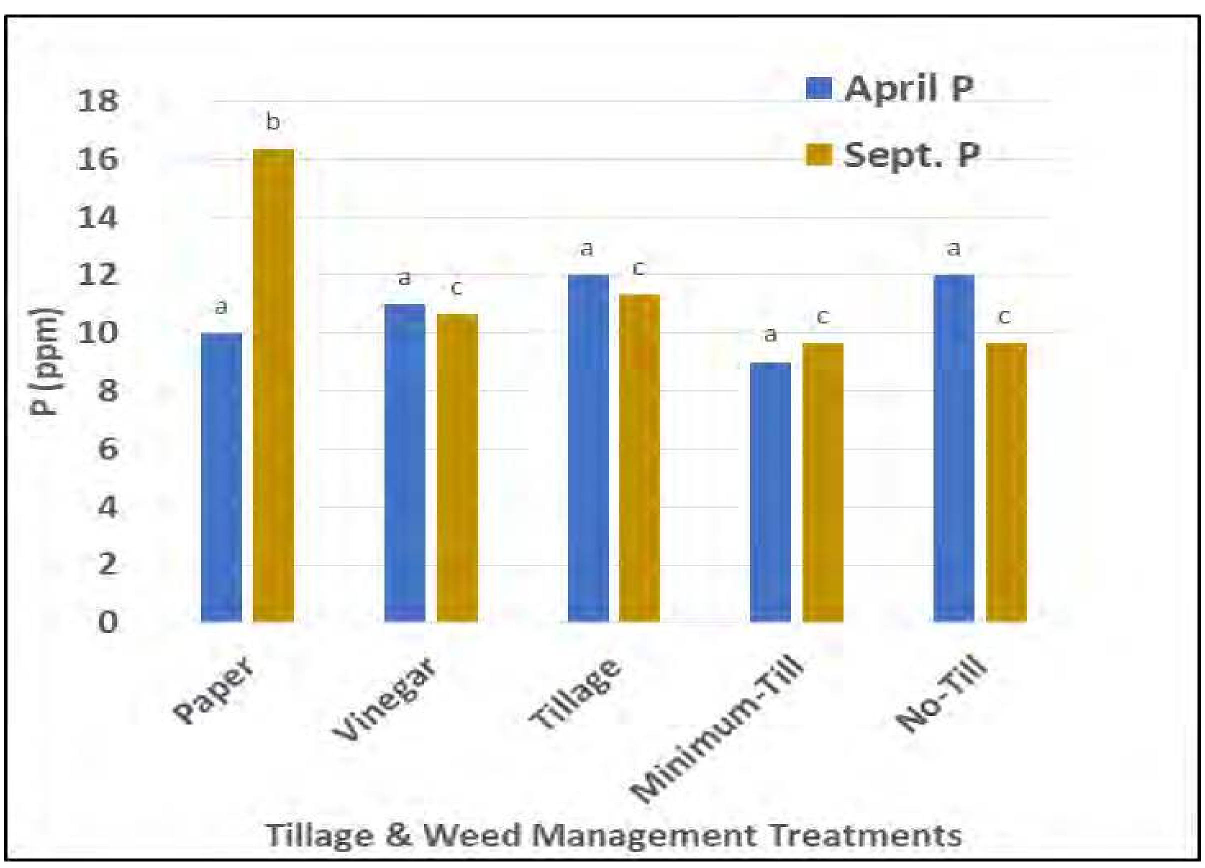

Figure 4. Phosphorus, bray 1, (P) levels in Brussels sprouts crop rows with 5 tillage and weed management treatments, 2007. Three random samples were taken in each treatment. All soil tests were taken from 0-10 inches with a 3/4-inch-diameter, 10-inch-long soil probe. Ten samples were taken, mixed in a bucket, and a two cup sample was sent for analysis. This was repeated for a total of 3 soil tests per treatment. Samples were analyzed by A & L Western Agricultural Lab, Modesto, CA. Treatments with different letters are significantly different ($p<0.05$).

CONCLUSIONS AND DISCUSSION

Perennial No-Till Living Mulch Row Middles Did Not Reduce Brussels sprouts In-Row Yield. The average yield of Brussels sprouts on mixed small acreage vegetable farms is reported as approximately 75 lbs. per 100 foot of row at crop space ranges of 24-36" by 14-24" (Stoner and Smith, 1978) or 0.25-0.38 lb. per square foot (Rabin et al., 2012). Using these yield comparisons, living mulch row middles did not reduce yields as long as long as vegetation competition (red clover and weeds) was managed in the crop row. Average per plant yields in the 4 experiment treatments that included weed suppression and/or tillage ranged from 0.63 to 1.4 lbs. (approximately 63-140 lbs. per 100' of double row at 24' by 24" spacing). However, the wide space left between crops as no-till clover row middles would likely decrease the *total per acre crop yield*. But, the benefits of living mulches between crop rows include reduced tillage, habitat for predators and parasites of insect pests, decreased annual weeds, regular addition of mowed plant residues to enhance nutrient cycling and build soil organic matter, and perennial, year-round living/growing roots providing habitat for rhizosphere microorganisms, such as the arbuscular mycorrhizae measured in this study. Other researchers report that no-till and reduced-tillage organic crop production systems resulted in enhanced annual weed control, improved soil health, increased soil microorganism abundance and diversity, and improved moisture conservation. (Creamer et al. 1996, Morse 1998, Keupper 2002, Ashford and Reeves 2003, Deguchi et al., 2007).

In-Crop-Row Tillage and Reduced Vegetation Cover Increased Soil Temperatures and Crop Yield: The earliest and highest average yield per plant seemed to be associated with higher soil temperatures and was recorded in spring-tilled/paper mulch plots (1.4 lbs.), followed by conventional tillage (1.1) and spring-tillage/vinegar plots (1.0).

Soil Health Measurements Were Decreased by Tillage: Arbuscular mycorrhizae and soil organic matter levels were highest in no-tillage and minimum-tillage plots and lowest in conventional tillage, tillage/vinegar plots, and tillage/paper mulch plots. In other research, increased soil organic matter levels were reported in reduced tillage/living mulch production systems (Kumwenda et al., 1993). In another study, white clover living mulch increased corn yields by facilitating arbuscular mycorrhizal fungus colonization and improving the phosphorus nutrition (Deguchi et al., 2007). However, other research indicates lower yields and crop competition in reduced tillage/living mulch systems (Creamer and Dabney 2002).

Associations between Yield and Soil Nutrient Levels, Both Early and Later in the Crop Growing Season Were Not Clear (Figure 5):

Phosphorus, bray 1 (P). Despite different crop yields, there was no difference in April soil P levels among weed/soil management treatments. In September, P was highest in tillage/paper mulch plots (which recorded the highest total yield and plant biomass) and lowest in tillage, and tillage/vinegar plots as well as in minimum-tillage and no-tillage plots (Figures 4 and 5). Despite similar soil P levels, lower yields were recorded in no- and minimum-tillage treatments. Soil P levels in 2007 experiment plots were low for best vegetable crop growth, both pre-plant in April and in September; recommended levels are generally in the 50 ppm range (Smith 2007, Sullivan et al. 2017). Soil P levels in all treatments were less than 18 ppm (likely due to no application of compost in 2007). Low P levels could be related to the low yields observed in no-tillage treatments, but P levels were also low in the higher yielding tillage/paper mulch and conventional tillage plots. In light of Biodesign Farm's high plant residue fertility system, it would have been interesting to test for organic P levels rather than using only bray P1 soil test methods. In one long-term study comparing inorganic and organic P fractions in tilled crops verses untilled pasture, permanent pasture soil had 29% higher total P than tilled crop soil; most of this was in the organic P fraction (Hedley et al. 1982). In most of Biodesign's vegetable production soils, where compost was added along with incorporated legume living mulch each spring, soil bray P1 levels were adequate to high, reaching excessive levels (>100 ppm) during the early 1990s when higher compost rates where applied. Biodesign soil test records 1993-2010 are available.

Nitrate-nitrogen (N). N soil levels were highest early in the season in all treatments that had been tilled and lowest in no-tillage plots. However, by July and until the end of the growing season in September, the highest N levels were in both paper mulch and minimum-tillage plots, though these plots recorded the highest and next to lowest yields (Figures 3 and 5). Spring soil N levels during early Brussels sprouts growth were sufficient for crop growth, even in the no-tillage plots, where average N levels were more than 40 ppm. On-farm research in California suggests that a soil nitrate-N level of 20 ppm or greater is sufficient to maintain maximum vegetable crop growth rates for several weeks in typical field conditions (Smith, 2007). Lower yields in minimum-tillage treatments did not seem to be caused by low soil N levels. It is possible that since the dominant vegetation in minimum-tillage plots was a nitrogen-fixing legume (red clover), soil N levels were not as negatively affected as they would have been by more N-competitive weed growth. Other reduced tillage research indicates that legumes generally have a tissue carbon: nitrogen ratio favorable to rapid decomposition and nitrogen mineralization compared with non-legumes (Creamer and Baldwin, 2000).

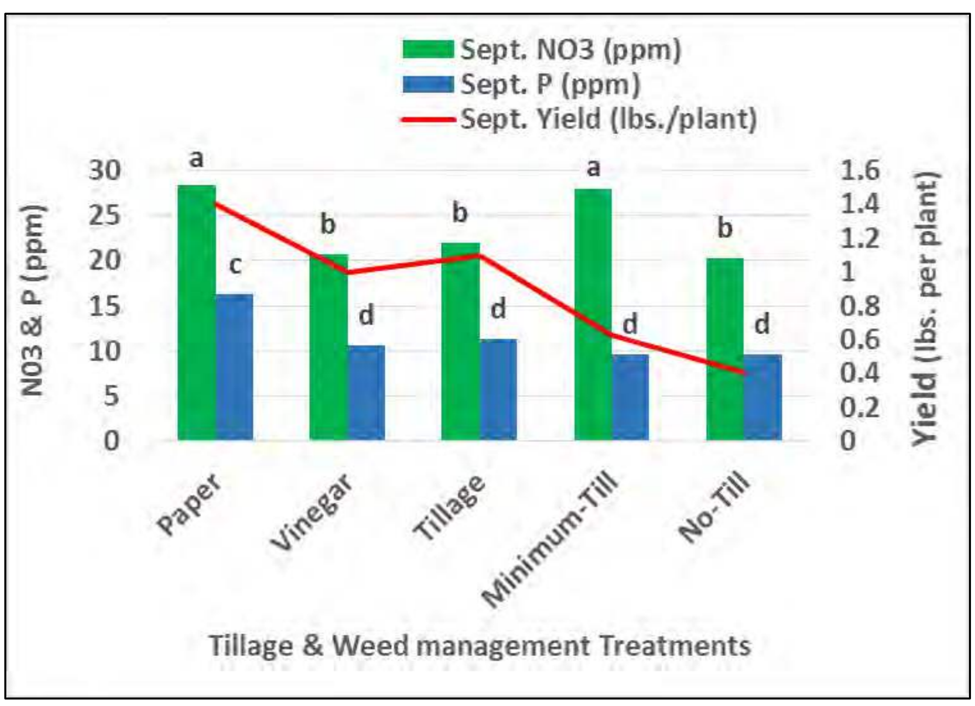

Figure 5. Comparison of Brussels sprouts yield with September nitrate-nitrogen (NO_3) and phosphorus, bray 1, (P) levels in crop rows with 5 tillage and weed management treatments, 2007.
Yield: Four plants were harvested per treatment replicate on 3 weekly dates in September, for a total of 12 plants, and sprout yield was recorded as average lbs. per plant. Differences among all treatments (except tillage and vinegar plots) were significant at $p < 0.05$).

Soil Tests: Three random soil samples were taken in each treatment. Samples were analyzed by A & L Western Agricultural Lab, Modesto, CA. Treatments with different letters are significantly different ($p<0.05$).

Environmental Factors Contributing to Lower Yields in Reduced and No- Tillage Treatments: Understanding which combination of environmental factors contribute to lower yields in no-tillage farming systems could help farmers mitigate those conditions while still utilizing no-tillage strategies. In Biodesign's farm system, lower yields in reduced and no-tillage treatments seem to be most clearly associated with lower soil temperature and increased vegetation cover. In other studies, regrowth of a rye cover crop competed with and reduced yields of organic vegetable crops (Cahn 2004), but yields were higher or the same in no-till vegetable plots compared with tilled/bare-soil plots (after summer cover crops) for lettuce (Wang et al., 2008) and broccoli (Abdul-Baki et al., 1997). Weed-crop competition (including poor crop establishment, increased crop diseases, and allelopathic effects of cover crops) decreased yields in several organic no-till studies (Emke 1985, Sturz et al. 1997, Keupper 2002, Creamer and Dabney 2002, Teasdale and Rosecrane 2003).

Tillage Affects Weed Species Dominance and Ecology: Fewer annual weeds were found in plots with less tillage. Tillage increased annual weed species compared to no-tillage where more perennial species were dominant. Over time, Biodesign's regularly mowed, no-till/perennial ground cover of legume living mulches between crop rows appeared to reduce populations of many annual weeds which were a problem and regularly managed on neighboring organic vegetable farms in Montana (using conventional tillage and cultivation for weed management). Other studies report decreased annual weeds in reduced tillage vegetable production (Creamer et al. 1996). However, over time at Biodesign farm (approximately 5 years), perennial broadleaf and grass weeds moved into untilled clover row middles. It may be necessary to till perennial, no-till row middles every 5 or 6 years.

SUMMARY and FUTURE DIRECTIONS

The many soil health and pest management benefits of Biodesign Farm's minimum-tillage/living mulch system support the farmer's efforts to continue with and to improve the system. Insect sprays were eliminated over time, likely because no-tillage living mulch row middles provide habitat for the abundant and diverse populations of pollen and nectar-requiring predator and parasite insects and ground-dwelling predators recorded during Biodesign's 2006 on-farm research. Other researchers have found that insect pest damage was lower in crops grown within living mulches and/or weeds (Dempster, 1969; Theunissen, 1994; Brandsæter et al., 1998; Hooks and Johnson, 2007; Bryant, 2013).

Biodesign's living mulch system also reduced, and with some crops, eliminated hand weeding and post-plant cultivation. Reduced weeding greatly diminished labor costs at Biodesign and helped to improve profitability. Weed suppression by living mulches has been observed in several studies (Ilnicki and Enache, 1992; Miura and Watanabe, 2002; Uozumi et al., 2004), but other researchers report increased crop competition in reduced tillage systems (Creamer and Dabney 2002).

Living mulches may also have helped reduce fertilizer applications at Biodesign Farm. Based on yield and soil organic matter/nutrient measurements in this experiment, nutrient levels were sufficient for crop production (except phosphorus), despite no fertilizer application beyond spring 2007 incorporation of a one-year-old red clover cover crop. Biodesign Farm's long-term soil test/amendment records support the premise that living mulches contributed to soil organic matter increases and increased soil nutrient levels, despite the farm's reduced compost/fertilizer applications after 2005.

Living mulches may have cultural benefits as well: at Biodesign, row middles were managed to provide shade and cooling during hot, dry spells and mowed short to enhance drying and increase ambient air temperatures during cool, wet periods. They also provided a windbreak for seedlings and transplants. However, Biodesign's 2007 experiment results indicate that permanent living mulches may cool spring soils, compete with crops, and reduce yields without in-crop-row weed suppression. Biodesign has also observed that living mulches enhance new pests, such as voles. Further, per acre crop yields may also decrease due to the land lost to crops for living mulches. Finally, most permanent living mulches require irrigation in hot, dry climates.

Biodesign is using on-farm experiment results and yield/pest records from 1993-2010 to help design a new farm system that balances economical yields with long-term soil health and pest suppression benefits, as well as reduced fertilizer, insect/disease/weed management, and soil preparation inputs/costs. The present farm design system utilizes no-till, perennial row-middle living mulches, spring in-crop-row minimum-tillage, and on-farm produced mulches (mowed living mulch blown into and/or applied to crop rows pre or post-planting, depending on the crop).

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CITATIONS

Abdul-Baki, A.A., Morse, R.D., Devine, T.E., Teasdale, J.R. 1997. Broccoli production in forage soybean and foxtail millet cover crop mulches. HortScience 32:836–839.
Ashford, D. and D. Reeves. 2003. A mechanical roller-crimper as an alternative kill method for cover crops. *Amer. J. Alternative Agric*. 18 (1): 37-45.
Brandsæter, L. O., J. Netland, and R. Meadow. 1998. Yields, weeds, pests and soil nitrogen in a white cabbage living mulch system. Biological Agriculture and Horticulture 16: 291–309.
Bryant, A. 2013. Influence of living and non-living habitat complexity on arthropods in strip-tilled cabbage fields. M.S. thesis. Michigan State University, East Lansing, MI. (Available online at: http://etd.lib.msu.edu/islandora/object/etd%3A1086/datastream/OBJ/view).
Cahn, M. 2004. Conservation Tillage and Cover Crop Systems for Organic Processing Tomatoes. Organic Farming Research Foundation Report: http://ofrf.org/.
Creamer, N.G., Bennett, M.A., Stinner, B.R., Cardina, J. 1996. A comparison of four processing tomato production systems differing in cover crop and chemical inputs. J. Amer. Soc. Hort. Sci. 121:559–568.
Creamer, N. and M. Dabney. 2002. Killing Cover Crops Mechanically: Review of recent literature and assessment of new research results. *Amer. J. Alternative Agric*. 17 (1): 32-40.
Creamer, N.G., Baldwin, K.R. 2000. An evaluation of summer cover crops for use in vegetable production systems in North Carolina. HortScience 35:600–603.
Deguchi S., Shimazaki, Y., Uozumi, S., Tawaraya, K., Kawamoto, H., Tanaka, O. 2007: White clover living mulch increases the yield of silage corn via arbuscular mycorrhizal fungus colonization. Plant Soil, 291, 291–299. doi:10.1007/s11104-007-9194-8.
Dempster, J. P. 1969. Some effects of weed control on the numbers of the small cabbage white (*Pieris rapae*) on Brussels sprouts. Journal of Applied Ecology 6: 339–345.
Hedley, M. J., J. W. B. Stewart and B. S. Chauhan. 1982. Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. Soil Science Society of America Journal. Vol. 46 No. 5, p. 970-976.
Ehmke, V. 1985. Does Straw Stifle Soybean Stands? *Soybean Digest*, May-June 1985. pp 40-41.
Hooks, C., and M. Johnson. 2004. Using under sown clovers as living mulches: Effects on yields, lepidopterous pest infestations, and spider densities in a Hawaiian broccoli agroecosystem. International Journal of Pest Management 50(2): 115–120. (Available online at: http://www.tandfonline.com/doi/abs/10.1080/09670870410001663462?src=recsys).
Ilnicki RD, Enache AJ 1992: Subterranean clover living mulch: An alternative method of weed control. Agric. Ecosyst. Environ., 40, 249–264. doi:10.1016/0167-8809(92)90096-T
Keupper, G. 2001. Pursuing Conservation Tillage Systems for Organic Crop Production. ATTRA – Organic Matters Series.
Kumwenda JTD, Radcliffe DE, Hargrove WL, Bridges DC. 1993: Reseeding of crimson clover and corn grain yield in a living mulch system. Soil Sci. Soc. Am. J., 57, 517–523. doi:10.2136/sssaj1993.03615995005700020036x
Miura S, Watanabe Y. 2002: Growth and yield of sweet corn with legume living mulches. Jpn. J. Crop Sci., 71, 36–42. (In Japanese with English summary). doi:10.1626/jcs.71.36.
Morse, R. 1998. No-till Production of Irish Potato on Raised Beds. *Vegetable Growers News* 5(6).
Morse, R. 2001. No-till Production. Organic Farming Research Foundation Report: http://ofrf.org/.
Rabin, J., Ginati, G., and Nitzsche, P. 2012. Yield Expectations for Mixed Stand, Small-Scale Agriculture. Rutgers New Jersey Agricultural Experiment Station. Volume 7, Issue 1 September.
Smith, R. 2007. Farm water quality planning project. PowerPoint presentation. University of California Cooperative Extension/USDA Natural Resources Conservation Service. (Available online at: http://cemonterey.ucanr.edu/files/85240.pdf)
Sorrenson,D. 1998. Economics of No-Till Compared to Traditional Cultivation Systems on Small Farms in Paraguay. Soil Conservation Project MAG/GTZ.
Stoner, A. and Norman J. Smith. 1978. Vegetables Are Appealing If You Don't Mind the Work. In: Living on a Few Acres. USDA Yearbook of Agriculture. Pages 199-209.
Sturtz, A., M. Carter, & H. Johnson. 1997. A Review of Plant Disease, Pathogen Interactions, and Microbial Antagonism under Conservation Tillage in Temperate Humid Agriculture. *Soil & Tillage Research* 41: 169 – 189.
Sullivan, D.M., E. Peachey, A.L. Heinrich, and L.J. Brewer. 2017. Nutrient Management for Sustainable Vegetable Cropping Systems in Western Oregon. Oregon state university extension service publication EM 9165. (Available online at: https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/em9165_0.pdf).
Teasdale, J. & Rosecrance. 2003. Mechanical Strategies for Killing a Hairy Vetch Cover Crop and Controlling Weeds in Minimum Tillage Corn Production.
Theunissen, J. 1994. Intercropping in field vegetable crops. Pest management by agrosystem diversification: An overview. Pesticide Science 42: 65–68.
Uozumi S, Deguchi S, Fushimi A., 2004: Optimal planting time of silage corn for the white clover living mulch system. Bull. Natl. Agric. Res. Cent. Tohoku Reg., 102, 93–100. (In Japanese with English summary).
Wang, G., Ngouajio, M., McGiffen M.E. Jr, Hutchinson, C.M. 2008. Summer cover crop and in-season management system affect growth and yield of lettuce and cantaloupe. HortScience 43:1398–1403.