Improving Conservation Tillage with Conservation Agriculture Practices

Josiah Marquez, Kelsey Mitsuda, Koon-Hui Wang
Plant and Environmental Protection Sciences, CTAHR, University of Hawai'i

The beginning of the era of conservation tillage

Due to the adverse environmental impacts of conventional tillage, especially of the environmental and human tragedies of the dust bowl in the 1930s, the U.S. federal government took the initiative to establish soil conservation. This concern was expressed clearly by President Roosevelt on February 26, 1947 who wrote: "The nation that destroys its soil destroys itself" (Baveye et. al., 2011). The dust storms notoriously called, "black blizzards" (Baveye et. al., 2011), were the result of moldboard plowing, which degraded the soil structure and caused soil erosion from wind and water runoff (Holland, 2004). Agronomists have studied the ill effects of tillage, including loss of soil moisture (Holland, 2004) and degradation of soil organic matter (Holland, 2004; Triplett and Dick, 2008) among many others that will be mentioned in the following.

Due to these adverse effects of conventional tillage, conservation tillage strategies were proposed by an extension worker, Edward Faulkner, in Ohio who published the book "Plowman's Folly" in 1942 (Lal, et. al., 2007). Since the 1950's, growers have been transitioning from moldboard plowing to reduced soil disturbance (Lal, et. al., 2007). This was later known by Conservation Technology Information Center (CTIC) as "reduced tillage" in the 1960's. CTIC defined reduced tillage as tillage that maintains 15-30% soil surface coverage by crop residue (Mitchell et. al., 2009). Due to the ambiguity of reduced tillage, the U.S. Soil Conservation Service in 1984 described conservation tillage as any tillage that aims at reducing water erosion by maintaining 30% crop residue coverage on soil surface or 1,000 pounds per acre (1,120 kg/ha) of residue (MWPS, 2000). Throughout the 1960's and 1970's, conservation tillage has gained ground through the availability of effective herbicides, no-till planters, and government policy incentives (Giller et. al., 2015). In the 1990's genetically-modified crops with herbicide tolerant traits helped to expand the adoption of conservation tillage (Giller et. al., 2015). In the 2012 Census of Agriculture, farmers' adoption of conservation tillage was apparent as United States had 35% of tillable land under no-till cultivation and 62% under some method of conservation tillage (Dobberstein, 2014).

Is conservation tillage profitable?

Profitability is dependent on yields and cost. No-till, a form of conservation tillage, has been associated with the additional inputs (and therefore increased costs) of cover crop seed and herbicides in a non-organic system compared to conventional tillage. However, conservation tillage reduces labor and time for tillage, unlike conventional tillage that usually requiring more tractor pass. In addition, conventional tillage can be hindered by precipitation resulting in delays in field preparation and waste of time and labor. Conservation tillage equipment often requires less power units and less maintenance, which results in lower costs than heavy tillage equipment (Triplett and Dick, 2008).

According to a comprehensive meta-analysis composed of hundreds of field experiments from 63 countries and 48 crops, no-till alone has resulted in 9.9% yield reduction. However, plots that integrated conservation agriculture principles with conservation tillage have been documented to have improved crop yields compared to those that only practice conservation tillage (Pittelkow et. al., 2015). Pittelkow et al. (2015) alluded to the fact that conservation tillage will only be profitable if operated in conjunction with conservation agriculture. The original aim of conservation tillage initiated in 1940s was to protect farms from the detriments of long-term soil degradation. However, it is important for one to realize that conservation tillage is not the only factor to remediate soil degradation. Therefore, the Food and Agriculture Organization (FAO) of the United Nations have proposed a new strategy called "conservation agriculture."

Conservation agriculture is a term coined by FAO, which entails three principles: 1) minimal soil disturbance; 2) continuous soil cover; and 3) crop rotation (FAO, 2015). FAO has taken the initiative to promote conservation agriculture as a worldwide plight in agriculture became apparent after the landmarked 1991 United Nations study, which estimated that soil in 552 million hectares of land, equal to 38% of today's global cultivated area, had been degraded to some degree by agricultural mismanagement since WWII (Gardner, 1997). USDA Natural Resource Conservation Services (NRCS) launched an "Unlock the Secrets in the Soil" movement and added the principle of continuous living roots as part of soil conservation practices (NRCS, 2013) as illustrated in Fig. 1. This is based on the understanding that living roots could provide nutrients for beneficial soil microorganisms that feed on sugar, organic acids, and amino acids through root exudates, hence a better way to maintain soil health. As defined by Doran (2000), soil health is the capacity of a soil to function within ecosystem boundaries to sustain biological productivity, maintain environmental quality, and promote plant and animal health.

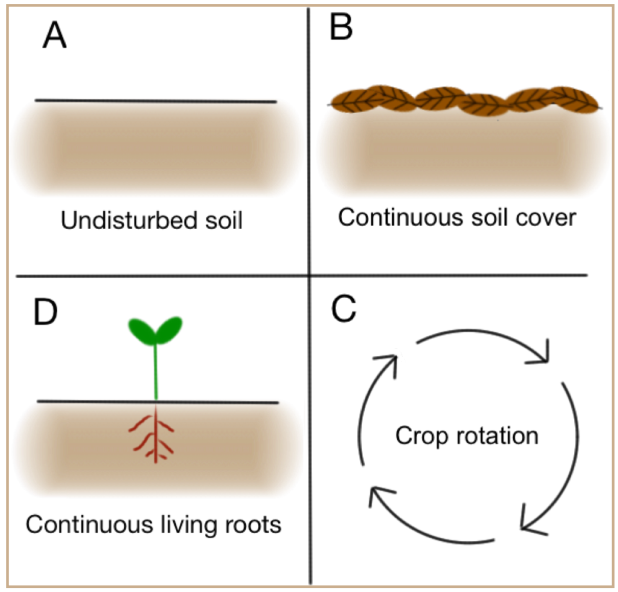


Fig. 1. The four conservation agriculture principles: A) minimal soil disturbance; B) continuous soil cover; C) crop rotation; and D) continuous living roots.

Fig 2. Roller crimper (A, B) is used at experiment stations at the University of Hawai'i to terminate various tropical legumes for no-till practice. Farmers often own a flail mower (C) to chop up crop residues above soil level (D) (photo credit: K.H. Wang).

The many approaches of conservation tillage

Conservation tillage are organized into four different approaches: no-till, strip-till, ridge-till, and mulch-till. **No-till**, also known as zero till, direct drilling (Holland, 2004) and chemical till (Lal, et. al., 2007), can be described as planting directly into the previous crop residue in the absence of any tillage. No-till has become the most popular conservation tillage method due to the availability of herbicides and genetically modified herbicide tolerant crops, drastically claiming new acreage in agriculture production (Lal, et. al., 2007). In large scale farming, no-till drill equipment is needed for the no-till operation. However, with the invention of the roller crimper by Rodale Institute in 2003 (MSU Extension, 2010), organic no-till has become feasible (Fig.2 A, B). Alternatively, farmers in Hawai'i improvise with a flail mower (Fig. 2 C, D) for no-till practice.

Strip-till involves a field having been tilled less than one third of the soil surface (Fig. 3 A), usually in narrow strips for planting (CTIC, 2002). This can be achieved by single or double tine-tiller (Fig. 3 B), or removing some blades from regular rotor-tiller (Fig. 3 C, D).

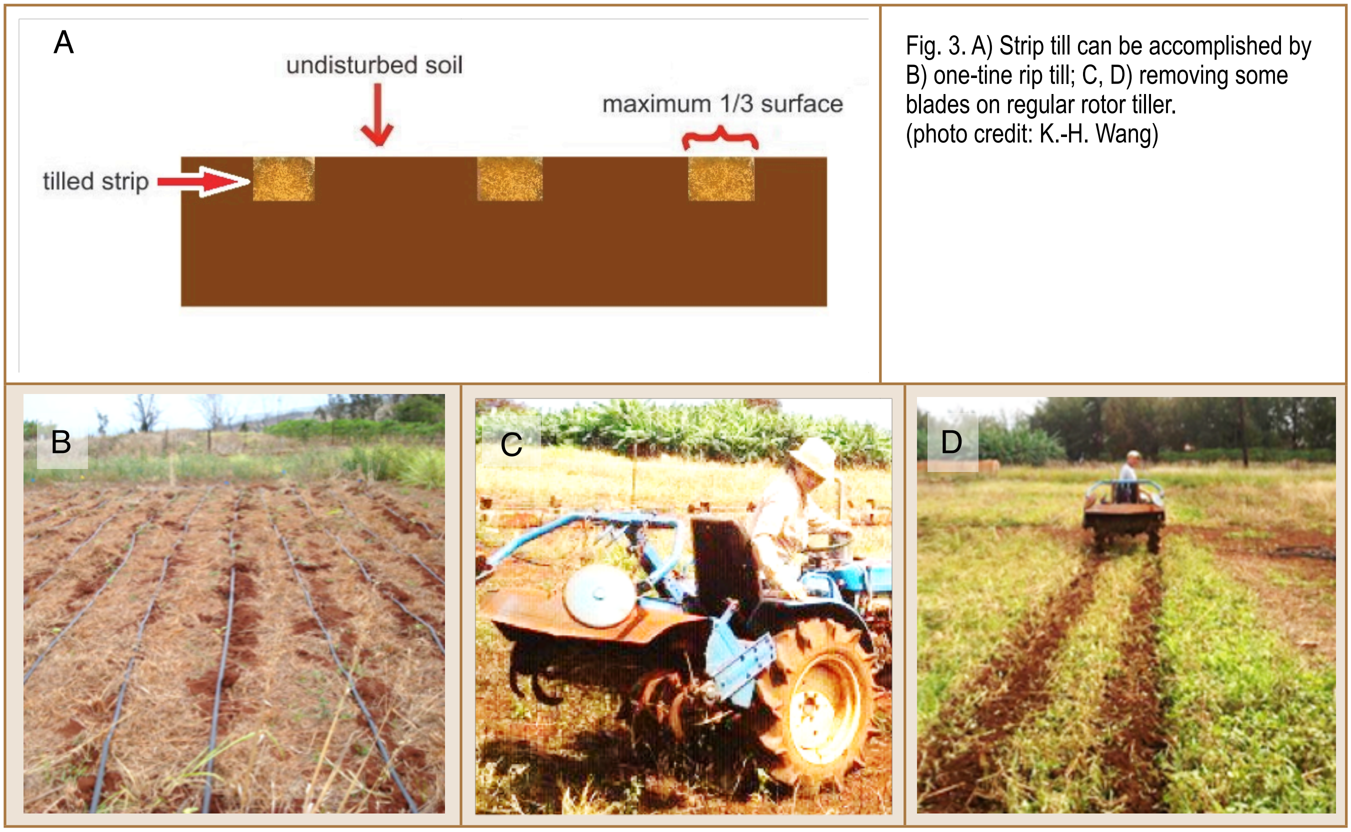


Fig. 3. A) Strip till can be accomplished by B) one-tine rip till; C, D) removing some blades on regular rotor tiller. (photo credit: K.-H. Wang)

Ridge-till involves creating ridges for crop planting, but only the top 2-4 inches of the ridge is sheared or tilled off to prepare for next crop planting (Fig. 4). The crop residues will fall off the ridge and cover the soil as surface mulch (Havin et. al., 2014; Mitchell, 2009). The ridges can be rebuilt with shallow tillage after several cropping cycles as the ridge become shallow (Brady and Weil, 2010). This method is able to control weeds with its combination of minimal tillage by shearing the ridge and spraying with herbicide (Kanwar et al., 1997). Ridge-till is favored in fields in which drainage is an issue or to provide a warmer seed bed for germination (Havin et. al., 2014).

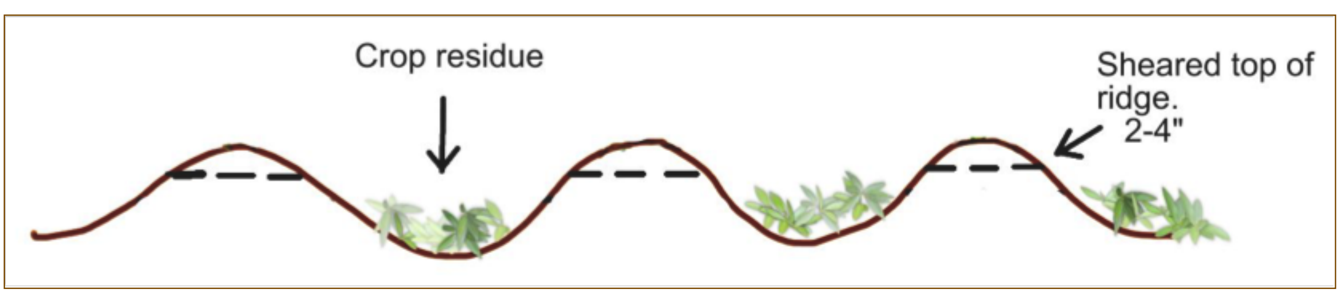


Fig. 4. Ridge till is performed by shearing off the top 2-4 inches of crop rows prior to crop planting.

Mulch-till consists of minimal tillage using conventional broadcast tillage implements (disks, chisel plows, rod weeders, and cultivators) with limited passes to maintain the minimal soil coverage of 30% (MWFS, 2000, Fig. 5). This is dated back to the 1930's using the chisel plow (Mitchell, 2009).

Fig 5. Minimal passes of the disk plow maintaining 30% soil coverage by crop residues (photo credit: K.-H. Wang).

Benefits of Conservation Agriculture

Since conservation tillage alone does not ensure yield improvement and could sometimes reduce crop yield more than conventional tillage (Pittelkow et. al., 2015), it is crucial that conservation tillage be practiced following the principles of conservation agriculture. The ultimate goal of conservation agriculture is to enhance soil health. A healthy soil should be able to support life processes such as plant anchorage and nutrient supply, retain optimal water and soil properties, and support soil food webs, recycle nutrients, maintain microbial diversity, remediate pollutants, and sequester heavy metals. Plant pathologists assert that disease suppression also should be a function of soil health (Wang and McSorley, 2005).

Fig. 6. A form of strip till and cover crop rotation system practiced in Hawaii where A) alternated stands of sunn hemp cover crop is mowed, and B) strip tilled into the soil, C) leaving alternating rows of sunn hemp as a living mulch that provides additional organic mulch on soil surface. D) The cash crop, zucchini, is then intercropped in between the strips of the sunn hemp living mulch (photo credit: K.-H. Wang).

One example of conservation agriculture illustrated in Fig. 6 where sunn hemp (*Crotalaria juncea*) cover crop was "**rotated**" with zucchini (*Cucurbita pepo*) crop. Alternate rows of sunn hemp were **strip-tilled** into soil, and the remaining rows were maintained as a living mulch to ensure "**continuous living roots**" in the system. Sunn hemp shoots of the living mulch were trimmed periodically to provide "**continuous soil cover**" in the zucchini agroecosystem. This conservation agriculture practice consistently increased zucchini yield compared to the conventional bare ground tilled system in two consecutive field trials conducted at Waialua, Oahu, HI (Wang et al., 2014).

Additional benefits of conservation tillage associated with conservation agriculture are listed below:

1. Reduced soil erosion

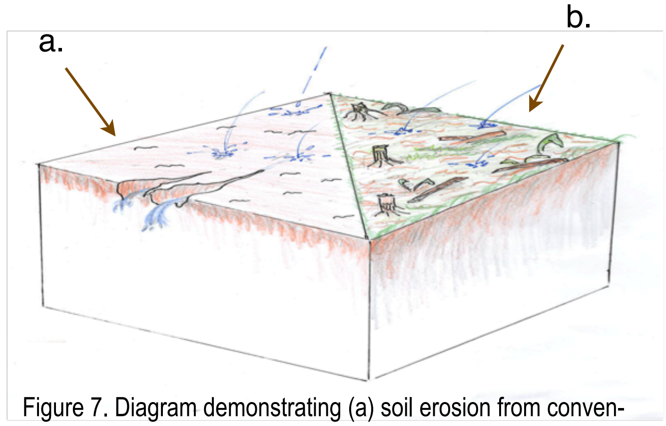


Figure 7. Diagram demonstrating (a) soil erosion from conventional tillage on the left and (b) soil retention from no-tillage on the right.

Topsoil is the most fertile layer of arable land. When intensive tillage is practiced, topsoil erosion can result in exposure of less productive subsoil which have poor physical, biological, and chemical properties with low organic matter, microbial activity, nutrient supply, infiltration, and plant available water (Havin et. al., 2014). Conservation tillage can greatly reduce erosion of the top soil by maintaining a vegetative cover over the soil, helping to maintain the soil structure and aggregation (Pimentel, 1995), and allowing more water infiltration (Triplett and Dick, 2008; Havin et. al., 2014). Planting with a no-till drill reduces soil erosion by up to 95%, and other conservation tillage methods reduce erosion by up to 68% (Towery, 1998). Reduction of soil erosion can also be improved with the conservation agriculture practice of continuous soil cover through crop rotation of cash crops and cover crops instead of leaving a field fallow, which will increase surface residue (Barly and Weil, 2010). Soil erosion is also reduced in conservation tillage by increasing soil organic matter that can improve aggregate stability (Peigne, 2007; Brady and Weil, 2010).

2. Increase soil organic matter and nutrient supply

Conventional tillage is known to increase soil organic matter (SOM) over time as crop residues on the soil surface is less intimately in contact with soil particles than residue homogenized in the soil by tillage. This will result in delayed decomposition of organic matter (Brady and Weil, 2010), while conventional tillage exposes the SOM to oxygen resulting in oxidative loss (Brady and Weil, 2010). Conservation tillage has increased soil carbon 8% compared to conventional tillage in the U.K. (Holland, 2004). Soil organic matter analysis following seven years of consecutive rotation between cash crops and cover crops in a conservation tillage system at the University of Hawaii Poamoho Experiment Station showed 14% increase in SOM (Fig. 8).

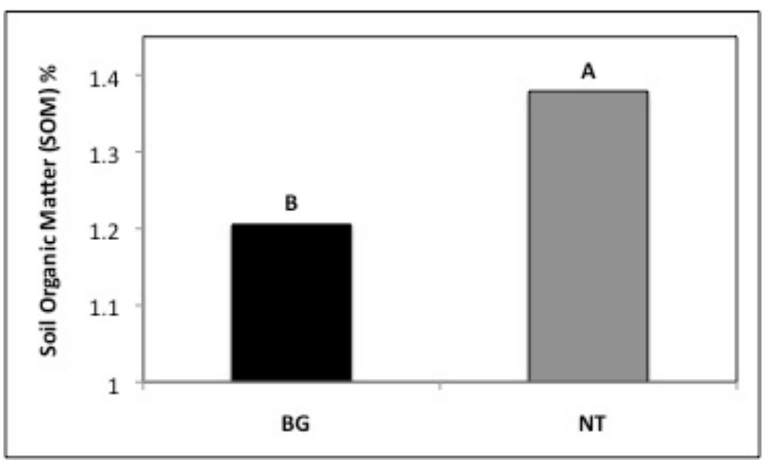
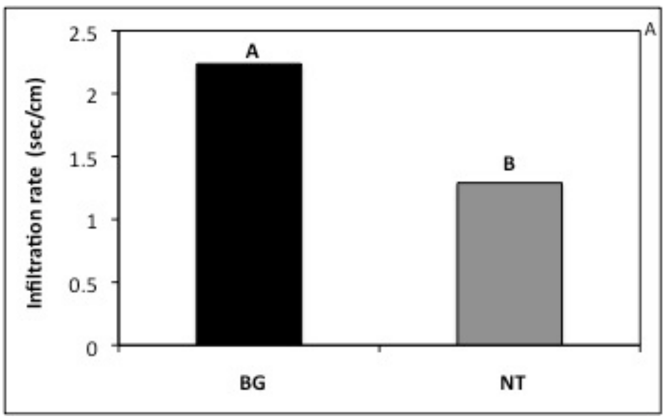


Fig. 8. Higher soil organic matter was detected after 7 consecutive years of no-till (NT) compared to conventional till with bare ground practice ($P < 0.05$) in an experimental plot at Poamoho Experiment Station, University of Hawai'i.

As SOM increases, soil aggregate stability was improved by 1) forming bridges between soil particles of silicate clays and iron and aluminum oxides; and 2) providing food for fungi and bacteria which exude polysaccharides and organic compounds that form sticky networks to bind soil particles together (Brady and Weil, 2010). In addition, SOM increases nutrient balance in the soil (especially of nitrogen, sulfur, and phosphorus) by 1) influencing soil microorganisms involved in mineralization or immobilization of soil nutrients (Havlin et. al., 2014); 2) contributing to 50-90% of soil cation exchange capacity that helps to exchange many important plant nutrients (Ca^{2+}, Mg^{2+}, K^{+}, NH^{4+}, etc..) with plant roots; and 3) chelating micronutrients to make them more readily available for plants (Brady and Weil, 2010).

3. Improve plant available water

Interestingly, in studies conducted in a dry climate under rain-fed agriculture, no-till increased yields 7.3% when conservation agriculture practices were integrated (Pittelkow et. al., 2015), suggesting that no-till gives plants an advantage in a water stressed environment. On the other hand, soil water is loss with conventional tillage. With every tillage pass, the available plant moisture in the soil can drop 0.25 inches (USDA, 2012). This is because conventional tillage destroys the structure of soil aggregates resulting in dispersed clay that clogs soil pores and forms a surface seal. When this surface seal dries after precipitation, it can form a hard soil crust resulting in high water runoff (Brady and Weil, 2010). Organic residue that cover the soil surface in conservation tillage 1) serves as a buffer to raindrop impact, and 2) can uphold higher water infiltration rates and reduce water runoff (Gebhardt et. al., 1985). This can be demonstrated by an infiltration test conducted in a seven consecutive years of no-till (NT) site at Poamoho Experiment Station (Fig. 9).



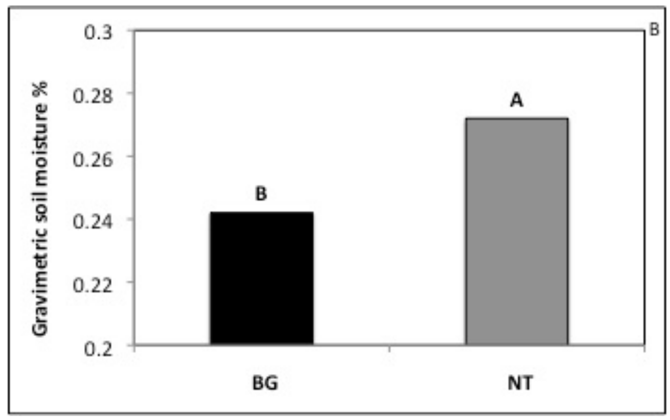


Fig. 9. Soil in no-till (NT) has A) faster infiltration rates ($P < 0.10$) and B) higher gravimetric soil moisture ($P < 0.05$) than tilled bare ground (BG) at the University of Hawaii Poamoho Experiment Station.

Organic surface mulch associated with conservation tillage systems also reduce soil temperature, thus reduce soil moisture evaporation. Organic mulch also increases SOM, leading to better soil aggregate and stability, improving water infiltration and water holding capacity. Therefore, crops in areas that experience water stress would benefit more from conservation tillage (Gebhardt et. al., 1985; Pittelkow et. al., 2015).

4. Enhancement of biological activity

Reduction in soil disturbance greatly improves soil biological activities including the abundance and richness of free-living nematodes, soil arthropods, earthworms and bacteria and fungi, all of which help to improve soil aggregation (Brady and Weil, 2010; Gebhardt et. al., 1985). Due to the enhancement of biological activity, nutrient cycling of nitrogen, sulfur, and phosphorus is also improved in conservation tillage system (Havlin et. al., 2014). Crop residue from practicing conservation tillage provides a more stable environment for diverse groups of natural enemies of pests, for example beetles and spiders (Schmidt et al., 2004; Pullaro et al., 2006). This biocontrol tactic will mitigate pest problems as demonstrated by conservation tillage research conducted in a green onion agroecosystem at the Poamoho Experiment Station (Quintanilla et al., 2016). Green onion planted in sunn hemp no-till plots surrounded by cowpea (*Vigna unguiculata*) and buckwheat (*Fagopyrum esculentum*) as insectary borders had a lower incidence of damage from thrips (*Thrips tabaci*), Liriomyza leaf miners, purple blotch (caused by *Alternaria porri*) as compared to conventional tilled bare ground (BG), soil solarization (Sol), or sunn hemp followed by solarization (SHSol) plots (Fig. 10).

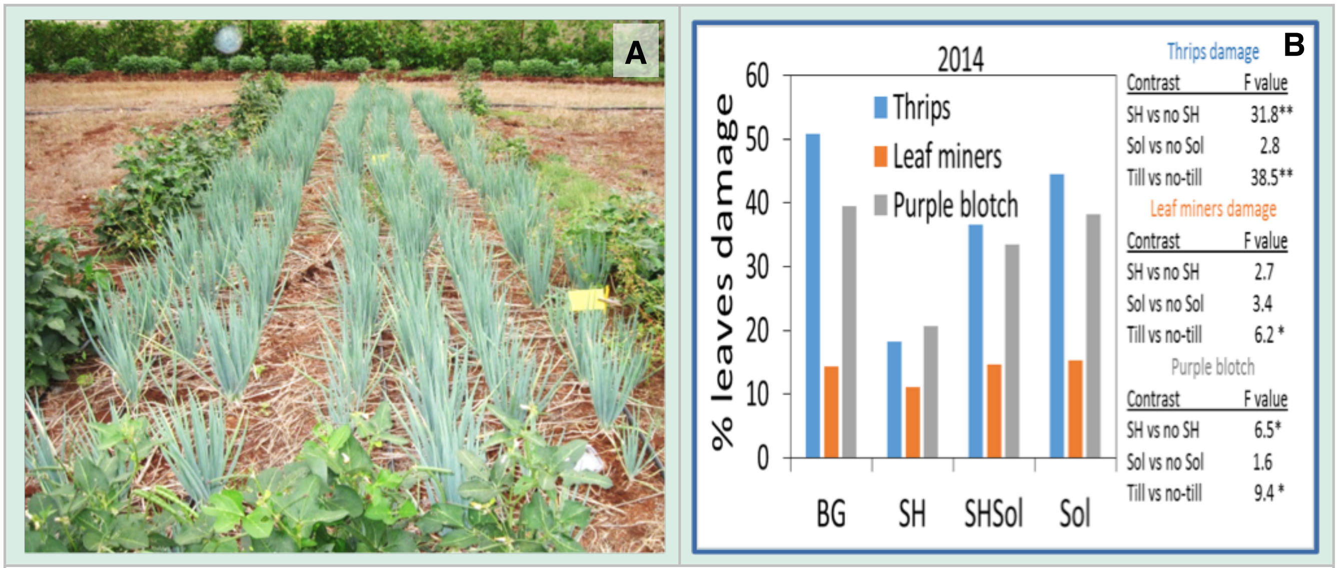


Fig. 10. A) Green onion planted in sunn hemp no-till plots surrounded by cowpea and buckwheat insectary borders, B) % leaves damaged by thrips, leaf miners and showing purple blotch symptom in sunn hemp no-till treatment compared to conventional till with bare ground (BG), soil solarization (Sol), or sunn hemp followed by solarization (SHSol). (photo credit: K.-H. Wang).

Besides enhancing soil macro-fauna, organic residue in reduced tillage help entomopathogenic fungi remain close to the soil surface and ready to infect insect hosts (Pell et. al., 2009). Meal worm larvae (*Tenebrio molitor*) baited into the seven-consecutive-year no-till (NT) site at Poamoho Experiment Station was more often infected with *Metarhzium anisopliae*, an entomopathogenic fungus (EPF) compared to conventional tillage (Fig. 11). *Metarhzium anisopliae* is an EPF used as an insect biological control. It has a broad insect host range, ubiquitous in the soil, and can survive on soil organic matter as a saprophyte in the absence of an insect host (Pell et. al., 2009).

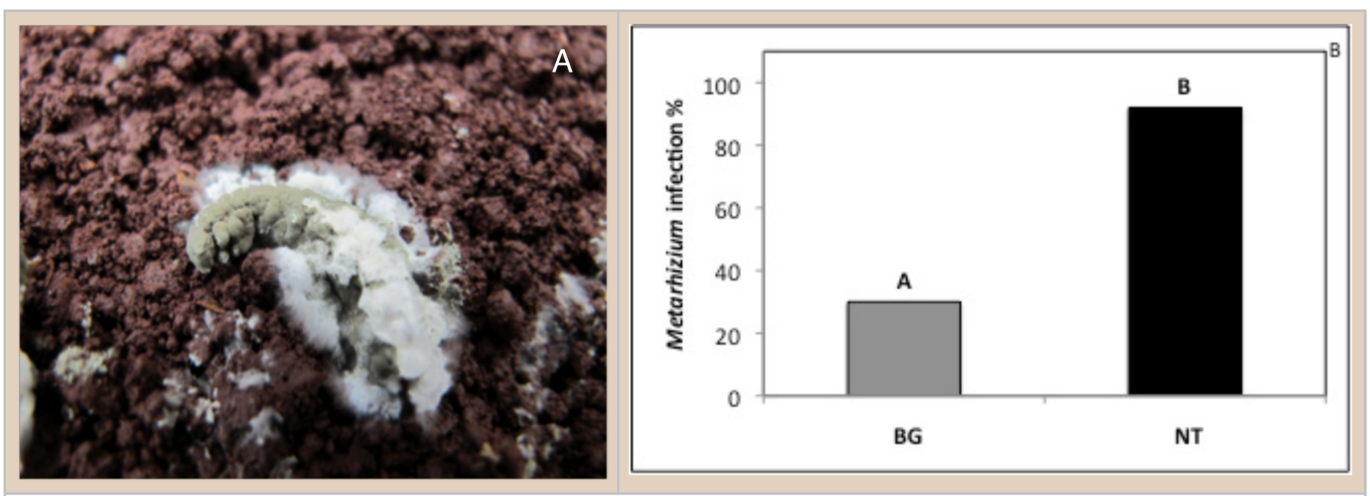


Fig. 11. A) Mealworm larvae (*Tenebrio molitor*) infected with entomopathogenic fungi (*Metarhzium anisopliae*) in the seven consecutive years of no-till (NT) site at Poamoho Experiment Station was B) higher in no-till (NT) than bare ground (BG) ($P < 0.05$) a in larvae bait assay for detection of entomopathogenic fungi (photo credit: J. Marquez).

5. Mycorrhizae

Conservation tillage has been reported to improve colonization of mycorrhizae due to reduced disturbance of the soil providing an environment for extraradical hyphae from host plants to become a main source of inoculum (Kabir, 2004). Arbuscular mycorrhizae fungi help plants to better absorb mineral nutrients and phosphorus (Mulligan et al., 1985) through a beneficial symbiotic relationship with plant roots. Proliferation of mycorrhizal fungi has been reported to protect plants from root pathogens (Thygesen et al. 2004), increase water use efficiency (Caravaca et al. 2004), while improving soil structure (Bethlenfalvay and Barea 1994; Kabir and Koide 2002). Mycorrhizal fungi have a wide host range. Thus, continuous living roots practiced in conservation agriculture provide host for the fungi, help these fungi to persist and proliferate in this agroecosystem (Scannerini and Bonfante-Fasolo 1983; Barea 1991).

Challenges of conservation tillage that can be reduced with conservation agriculture

1. Weed management

Although conservation tillage along with stale seedbed management such as herbicide application at post-plant could reduce weed seed banks over time (Murphy, 2006), weeds might be a problem following conservation tillage if there is not sufficient crop residue as a surface mulch to suppress weeds (Miller and Nalewaja 1985; Wiese 1985; Froud-Williams 1988) (Fig. 12). Applying the conservation agricultural principle of continuous soil cover can help reduce this risk.

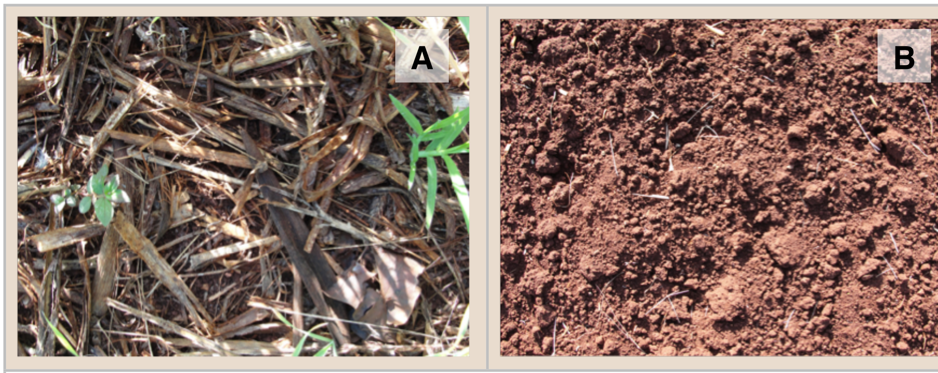


Fig. 12. A) No-till with soil coverage from corn residues showing the needs of additional weed control, unlike B) conventional tillage would temporarily desiccate weeds (photo credit: J. Marquez).

2. Plant pathogens and pest

Pathogens can survive in the soil and/or the crop residue associated with conservation tillage. This is especially a challenge if conservation tillage is practiced with monoculture and intensive use of pesticides without a proper pesticide rotation program (Bockus and Shroyer, 1998). However, in conservation agriculture system, enhancement of a broad range of soil microorganisms could support natural enemies of soilborne or residue-borne pathogens (Bockus and Shroyer, 1998). Wang and Hooks (2014) reported an increase in the abundance of predatory nematodes and nematode-trapping fungi on eggplant following sunn hemp and oat (*Avena sativa*) cover cropping in a no-till system, both of which are natural enemies of plant-parasitic nematodes.

Fig. 13. Oil radish as cover crop.

3. Soil Compaction

Although conventional tillage could quickly loosen up compacted soil, soil compaction can quickly re-form as tillage weakens the soil structure (Brady and Weil, 2010). Thus it is important to practice conservation tillage through conservation agriculture with continuous soil cover and living roots. While enhancement of microbial densities in conservation agriculture system could improve soil aggregation and soil structure, planting a cover crop with a deep tap root system such as the oil radish (*Raphanus sativus*) followed by no-till practice have been demonstrated to increase water infiltration, reduce soil erosion, and reduce soil compaction by breaking up the soil (Alberts and Neibling, 1994). Some oil radish varieties were sold as "tillage radish," with taproot growth to depths of 6 feet or more. As the oil radish cover crop is terminated, their thick taproots would leave behind big soil pores that will improve soil tilth and break up surface soil compaction (USDA, 2009).

Conclusion

Besides U.S. mainland, conservation tillage has been gaining new grounds internationally in Australia, South America, Canada, (Triplett and Dick, 2008) Europe (Holland, 2004), Africa (Giller et. al., 2015), as many have recognized the benefits of this cultural practice. In fact, Argentina and southern Brazil are making significant progress in expanding no-till acreages as thousands of small-scale soybean and corn farmers are adapting cover-crop-based no-till agriculture with animal tractors and small tractors (Brady and Weil, 2010). Many have described conservation tillage as a kind of agricultural revolution, but more awareness is now focused on the importance of conservation tillage through conservation agriculture.

REFERENCES

Baveye P.C., Rangel D., Jacobson A.R., Laba M., Darnault C., Otten W., Radulovich R., Camargo F.A. 2011. From dust bowl to dust bowl: soils are still very much a frontier of science. Soil Science 75: 2037-2048.

Bockus, W. W., and J. P. Shroyer. 1998. The impact of reduced tillage on soilborne plant pathogens. Annual Review of Phytopathology 36: 485-500.

Brady N.C.and Weil R.R. 2010, Elements of the nature and properties of soils. New Jersey: Prentice hall.

CTIC. 2002. National crop residue management survey. Conservation Technology Information Center,West Lafayette, IN. http://www.ctic.purdue.edu/media/pdf/ TillageDefinitions.pdf (Accessed on May 31, 2016).

Doran, J. W., M. R. Zeiss. 2000. Soil health and sustainability: managing the biotic component of soil quality. Applied Soil Ecology 15: 3-11.

Dobberstein, John. No-till movement in U.S. continues to grow. (August 1, 2014). No-till farmer. https://www.no-tillfarmer.com/articles/489-no-till-movement-in-us-continues-to-grow (Accessed May 18, 2016).

FAO (Food and Agriculture Organization of the United Nations). 2015. Conservation agriculture. http://www.fao.org/ag/ca/index.html (Accessed May 31, 2016).

Gardner, G. 1997. Preserving global cropland. Pp. 42-59 in Starke, L. (Ed.). State of the World 1997: A Worldwatch Institute Report on Progress Toward a Sustainable Society. W.W. Norton and Company, New York.

Gebhardt, M. R., T. C. Daniel, E. E. Schweizer, and R. R. Allmaras. 1985. Conservation tillage. Science 230: 625-630.

Giller K.E., Andersson J.A., Corbeels M., Kirkegaard J., Mortensen D., Erenstein O., Vanlauwe B. 2015. Beyond conservation agriculture. Frontiers in Plant Science 6: 870.

Havlin J., Beaton J.D., Tisdale S.L., Nelson W.L. 2014. Soil fertility and fertilizers: An introduction to nutrient management. 8th ed. Pearson Prentice Hall, Upper Saddle River, NJ.

Holland J. 2004. The environmental consequences of adopting conservation tillage in Europe: reviewing the evidence. Agriculture, Ecosystems & Environment 103: 1-25.

Kabir, Z., 2005. Tillage or no-tillage: Impact on mycorrhizae. Canadian Journal of Plant Science 85: 23-29.

Kabir, Z. and Koide, R. T. 2002. Mixed cover crops, mycorrhizal fungi, soil properties and sweet corn yield. Plant Soil 238: 205–215.

Kanwar, R. S., T. S. Colvin, and D. L. Karlen. 1997. Ridge, moldboard, chisel, and no-till effects on tile water quality beneath two cropping systems. Journal of Production Agriculture 10: 227.

Lal R., Reicosky D., Hanson J. 2007. Evolution of the plow over 10,000 years and the rationale for no-till farming. Soil and Tillage Research 93: 1-12.

Mitchell J. 2009. Classification of conservation tillage practices in California irrigated row crop systems. University of California, Agriculture and Natural Resources, Oakland, CA.

Michigan State University (MSU) Extension. 2010. About the cover crop roller/crimper. http://covercrops.msu.edu/crimper/about.html (Accessed June 6, 2016).

Mulligan, M. F., Smucker, A. J. M. and Safir, G. F. 1985. Tillage modifications of dry edible bean root colonization by VAM fungi. Agronomy Journal 77: 140–144.

Murphy, S. D., D. R. Clements, S. Belaoussoff, P.G. Kevan, and C.J. Swanton. 2006. Promotion of weed species diversity and reduction of weed seedbanks with conservation tillage and crop rotation. Weed Science 54: 69-77.

MWPS (MidWest Plan Service). 2000. Conservation Tillage Systems and Management. 2nd ed. MWPS-45. Ames, IA. https://www-mwps.sws.iastate.edu/catalog/crop-production/conservation-tillage-systems-and-management (Accessed June 6, 2016).

NRCS (Natural Resources Conservation Service). (2013). Soil health key points. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1082147.pdf (Accessed May 31, 2016).

Peigné, J., B. C. Ball, J. Roger-Estrade, and C. David. 2007. Is conservation tillage suitable for organic farming? A review. Soil Use and Management 23: 129-44.

Pimentel, D., C. Harvey, P. Resosudarmo, K. Sinclair, D. Kurz, M. Mcnair, S. Crist, L. Shpritz, L. Fitton, R. Saffouri, and R. Blair. 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267: 1117-123.

Pullaro T.C., Marino P.C., Jackson D.M., Harrison H.F., Keinath, A.P. 2006. Effects of killed cover crop mulch on weeds, weed seeds, and herbivores. Agriculture, Ecosystems and Environment 115: 97–104.

Quintanilla-Tornel, M.A., K.-H. Wang, J. Tavares, C.R.R. Hooks. 2016. Effects of mulching on above and below ground pests and beneficials in a green onion agroecosystem. Agriculture, Ecosystems, and Environment 224: 75-85.

Scannerini, S. and Bonfante-Fasolo, P. 1983. Ultrastructure analysis of mycorrhizal associations. Canadian Journal of Botany 61: 917–943.

Schmidt MH, Thewes U, Thies C, Tscharntke T. 2004. Aphid suppression by natural enemies in mulched cereals. Entomologia Experimentalis et Applicata 113: 87- 93.

Thygesen, K., Larsen, J. and Bodker, L. 2004. Arbuscular mycorrhizal fungi reduce development of pea root-rot caused by Aphanomyces euteiches using oospores as pathogen inoculum. European Journal of Plant Pathology 110: 411–419.

USDA (United States Department of Agriculture). 2009. Radishes: A new cover crop option. American Society of Agronomy. http://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/nrcs142p2_022940.pdf (Accessed June 6, 2016).

USDA (United States Department of Agriculture). 2012. No-till farming critical for preventing loss of soil moisture during drought conditions. Available online at: http://www.nrcs.usda.gov/wps/portal/nrcs/detail/ia/home/?cid=nrcs142p2_011847 (Accessed June 6, 2016).

Wang, K.-H, and C.R.R. Hooks. 2014. Benefits of mix cover cropping on soil health. Journal of Nematology 46: 254 (abstract).

Wang, K.-H. and R. McSorley. 2005. Effect of soil ecosystem management on nematode pests, nutrient cycling, and plant health. APSnet Plant Pathology Online, St. Paul, MN. Jan 19, 2005.

Wang, K.-H., T. Radovich, A. Pant, and Z. Cheng. 2014. Integration of cover crops and vermicompost tea for soil and plant health management in a short-term vegetable cropping system. Applied Soil Ecology 82: 26-37.

ACKNOWLEDGEMENTS

This project is in part supported by NRCS CIG 69-9251-15-957, USDA NIFA 2013-04774, and CTAHR Supplemental Fund 9022H. This is a collaborative work with CTAHR Sustainable and Organic Agriculture Program (SOAP).