Challenging the paradox of conservation agriculture and weed management

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The core principles of conservation agriculture (CA) are maintenance of soil cover, crop rotation, and planting with minimal soil disturbance (Pittelkow et al. 2015). In theory, these principles of CA should also improve the management of weeds. This is because the practices of maintaining soil covered with residues and/or living cover crops and rotating crops are important components of integrated weed management (Liebman and Gallandt 1997; Liebman and Davis 2000). Similarly, because agricultural weeds tend to be early successional species, i.e., opportunists that rapidly colonize and are adapted to disturbed environments, the reduction in soil disturbance associated with CA should be expected to reduce the opportunities for weeds to colonize and persist in these systems (Froud-Williams et al. 1984; Mulugeta and Stoltenberg 1997). In reality, however, weed pressure in CA systems tends to be higher, rather than lower, compared to conventional systems where these principles are not followed, and this often necessitates reliance on pesticides that undercut the environmental benefits of CA. Grower concerns over less than satisfactory weed control also likely limit wider-spread adoption of CA (Brainard et. al. 2016). Addressing this apparent paradox—that weed management is more challenging in CA despite the fact that the principles of CA should in theory reduce weed abundance—requires understanding the ecological role of weeds in agroecosystems, the factors that drive their abundance and success, and the role that other management practices often "bundled" with CA may play in undermining weed control (Giller et al. 2015). In so doing, we emerge with a framework for diagnosing the limitations of current CA systems with regard to weed management and for developing new strategies for CA that effectively suppress, rather than encourage, weed establishment and growth.

Understanding the ecological role of weeds in agroecosystems requires acknowledging that weeds are, in large part, a consequence of how we practice agriculture. Two aspects of how we practice agriculture strongly influence weed abundance and growth. The first is disturbance associated with the planting, cultivation, and harvesting of crops. Nearly all agricultural practices involve some degree of disturbance, either in the form of mechanical soil disturbance or chemical disturbance (i.e., herbicides). While these types of agricultural disturbance are often used to kill weeds, they also create the conditions necessary for subsequent weed re-colonization and growth by initiating the ecological process of *secondary succession*. Secondary succession is the sequential colonization by plants of bare soil following a disturbance (Odum 1969). The first of these early successional species are the plants we typically think of as "weeds". Hence, because they involve frequent disturbance, our agricultural management practices frequently re-initiate the process of secondary succession, and thereby the colonization and establishment of weeds (Smith 2015).

The second aspect of agriculture that impacts weed abundance and growth is the relatively high availability of resources within crop fields. Because weeds are plants, they require the same basic resources that all plants need, namely space in which to establish, water and nutrients from the soil, and light to carry out photosynthesis (Silvertown 2004). Most weeds are adapted to effectively exploit available resources, which enables them to grow and reproduce rapidly. In addition, the disturbances that initiate succession also help to ensure that these resources are available at the same time that weeds have the highest demand for them, i.e., in the early stages of their growth (Liebman and Davis 2000). Therefore, as long as our agricultural practices continue to involve disturbance to the soil in ways that stimulate weed emergence, and as long as our cropping systems are not completely effective in making use of all available light and soil resources throughout the growing season, weeds will continue to be a persistent management challenge to agriculture.

Given this insight, we can formulate a simple conceptual model in which disturbance and resource availability interact to determine the weed pressure in a given cropping system. Disturbance, occurring either via tillage/cultivation or herbicides, removes actively growing plants from a given area of soil. This initiates weed emergence and colonization via secondary succession. Resource availability then determines how quickly this succession proceeds (i.e., how fast weeds establish, grow, and reproduce). According to this model, we would expect the highest weed abundance to occur in cropping situations where both of these factors, disturbance and resources, are at maximum levels (i.e., the spatial extent of the disturbance event is high and resource availability is also high). Consequently, we would also expect the need for weed control, and by extension the externalities associated with the weed control practices, to be highest under these same conditions (Smith 2015).

In contrast, intermediate weed abundance would be expected to occur in cropping situations where one of these factors, disturbance or resources, is at a relatively high level but the other is at a relatively low level. Under these situations, weed abundance is limited to some extent due to either a reduction in weed colonization and establishment or subsequent weed growth and fitness. Lastly, a cropping situation in which both of these factors are at low levels would be expected to lead to the lowest weed abundance relative to the other situations. In this situation, not only are the opportunities for weeds to emerge and establish minimized, but any weeds that do establish are quickly starved of resources, ideally by a robust and thriving crop that efficiently makes use of the resources that are available to it.

The conceptual framework described above allows us to categorize different CA systems with regard to their levels of disturbance and resource capture and suggests that weed problems in CA systems arise, in large part, because either one or both of these factors are not being adequately addressed at the system-level. We know, for example, that conservation tillage practices associated with CA range in intensity and frequency of disturbance, and that even no-till planting results in disturbance levels that are sufficient to stimulate weed emergence from the soil seed bank (Reicosky 2015; Theisen and Bastiaans 2015). Similarly, CA systems are often no more efficient at capturing resources than are their conventional counterparts (Giller et al. 2015; Pittelkow et al. 2015). Hence, the challenge for improving weed management in CA is to address the sources of disturbance and resource availability at the system-level in a concerted effort to move CA systems toward conditions of lower weed abundance, ideally with less reliance on herbicides.

While this may seem like a daunting challenge, recent research provides several relevant examples of how CA systems can be modified in ways that improve not only weed management outcomes, but also crop yields and overall profitability (Davis et al. 2012; Harker et al. 2016). In some cases, even relatively simple changes to a cropping system can result in dramatic reductions in both soil disturbance (Theisen and Bastiaans 2015) and resource availability (Borger et al. 2010; 2016), resulting in substantial reductions in weed abundance and fecundity. Such changes will be necessary if CA systems are to achieve wider-spread adoption among farmers and reductions in their overall impact on the environment.

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