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Predictive modelling of weed seed movement in response to superficial tillage tools

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ABSTRACT

Weed seed burial and excavation by tillage determines seed depth, seed survival, germination and pre-emergent seedling mortality. However, quantitative estimates of seed burial are available for only a few tools and often without reference to soil structure, moisture or tillage depth. This study proposes a conceptual model for predicting weed seed movements during superficial tillage in response to the type of tool, tillage depth and soil structure. The proposed model was calibrated with field data collected using coloured plastic beads as weed seed proxies. Beads were placed at different vertical and horizontal positions before tillage, using augers to preserve soil structure and collected after tillage by opening trenches and counting beads found at different depths. Approximately 33% of the beads were retrieved and used to establish bead distributions from which model parameters were estimated. Cross-validation showed that prediction quality was satisfactorily (modelling efficiency = 0.85, minimum rMSEP = 0.11) with most of the error associated with using a harrow in compacted soil. Subsequently, the new model was integrated into the existing weed dynamics model FlorSys, and simulations were run to predict weed emergence and dynamics for different tillage practices. With a surface seed bank, total emergence was highest for shallow operations (harrow, discs) and lowest for deep operations (chisel, mouldboard plough). Emergence was also lower in compacted soils. Differences among tillage tools persisted when weed dynamics were simulated over several years, with mouldboard ploughing generally having the lowest density even though this tool was only used every three years. Superficial tillage which left seeds closest to the soil surface resulted in the highest weed density. Also, for species with heavy seeds densities generally increased with ploughing. These simulations confirm the utility of the new model, but additional studies are needed to examine other tillage, management practices and weed species combinations.

1. Introduction

Since the onset of agriculture, a large part of crop management, particularly tillage, aimed at eliminating weeds (e.g. *Oeconomicus* by Xenophon ca. 375 BC, *De Re Rustica* by Lucius Junius Moderatus Columella ca. AD 42), both by making the seed bank germinate at a time when the resulting plants would not hinder the crop and by eliminating weed plants at those times they would compete with the crop. Recently, with development of conservation tillage[1], tillage has gradually been simplified or even abandoned to reduce fuel consumption, work load or soil erosion (Derpsch and Friedrich, 2009); this practice is often facilitated if herbicide-tolerant varieties are available (e.g. Givens et al., 2009) but has been reported to increase weed infestations (e.g. Chauvel et al., 2001; Cirujeda et al., 2003) and/or change flora composition (Carter and Ivany, 2006; Légère and Samson, 2004; Murphy et al., 2006; Stevenson et al., 1997).

Tillage is of the main drivers of seed bank and emergence processes, which are essential for weed reproduction (Forcella et al., 2000). It increases soil fragmentation, depending of the tool as well as soil texture and moisture (Chatelin et al., 2005; Hillel, 1971; Hughes and Baker, 1977; Roger-Estrade et al., 2000b), and thus reduces pre-emergent seedling mortality (Colbach et al., 2006; Dorsainvil et al., 2005; Dürr and Aubertot, 2000; Vleeshouwers and Kropff, 2000). Tillage is also the main factor for seed burial and excavation, thus determining seed depth and

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[1] Any minimal tillage system that leaves the soil surface at least 30 percent covered by crop residue (Fawcett and Towery, 2004).

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subsequent seed germination (Benvenuti et al., 2001; Colbach et al., 2006) as well as pre-emergent seedling mortality (e.g. Benvenuti et al., 2001; Chancellor, 1964). In un-tilled fields, seeds tend to remain on or close to soil surface (Bàrberi and Lo Cascio, 2001; Clements et al., 1996), even though weed seeds are partially buried by natural processes (e.g. Mohler et al., 2006; Westerman et al., 2009). Conversely, tillage buries seeds at a depth where they are less prone to macro-predation (by birds, insects, rodents, etc.) and germination (e.g. Baraibar et al., 2009; Puricelli et al., 2005) and thus persist longer (Mohler and Galford, 1997; Omami et al., 1999; Sanchez del Arco et al., 1995). The degree of seed burial greatly varies with the tool, the tillage depth and environmental conditions (Colbach et al., 2000; Cousens and Moss, 1990; Gruber et al., 2010; Grundy et al., 1999; Roger-Estrade et al., 2001) but, in contrast to natural seed burial, not with seed morphology (e.g. Moss, 1988).

It is therefore essential to improve our understanding of the effect of tillage on seed bank movements in order to define efficient soil management rules for weed control, leading to a decrease in chemical herbicides. This is the reason why many weed demography models include sub-models describing the effect of tillage on seed bank dynamics (see reviewers by Colbach and Debaeke, 1998; Holst et al., 2007). Seed movement during mouldboard ploughing has been successfully modelled with mechanistic models based on ploughing characteristics (depth, width, presence of a skim-coulter) and initial soil structure (Colbach et al., 2000; Roger-Estrade et al., 2001). However, for the numerous superficial tillage tools used by farmers, only a few, empirical seed movement matrixes are available (e.g. Cousens and Moss, 1990; Mead et al., 1998). These authors divided the seed bank of the tilled layer into several 3–5-cm-thick sub-layers and estimated the proportion of seeds moved between layers from statistical relationships observed in one experimental situation. The resulting transfer matrixes were calculated for a small number of contrasting tools (e.g. power harrow, spring tine, chisel) working at depths exceeding 15 cm in a single soil texture and structure. They can thus not be extrapolated to other soil textures and structures or to variations in tillage tools and depths. Moreover, these authors introduced their weed seed proxies (plastic beads) by opening trenches in the field, disturbing the soil structure and thus interfering with soil and seed displacement during tillage; they recovered the beads with samples taken with an auger, thus only retrieving a small proportion of the beads. In the past, our team (Colbach et al., 2000; Roger-Estrade et al., 2001) developed a different method, introducing the same weed seed proxies with a 4-cm diameter auger in a small number of well chosen locations, preserving soil structure; after tillage, the beads were retrieved by opening trenches upstream from the initial bead location and then successively counting beads at different depths and removing soil in the direction of the tractor movement.

Consequently, our objectives were (1) to propose a conceptual model for predicting weed seed movements during superficial tillage in response to the type of tool, tillage depth and soil structure based on our knowledge of physical processes occurring during tillage, and (2) to calibrate and evaluate this model in a field experiment, using the method developed in the previous ploughing experiment (Colbach et al., 2000; Roger-Estrade et al., 2001). Moreover, (3) to illustrate its application, the new seed movement model was integrated into an existing weed dynamics model, and (4) simulations were run to predict weed emergence and dynamics for different tillage practices. For this purpose, the FlorSys model was chosen (Colbach et al., 2014; Gardarin et al., 2012; Munier-Jolain et al., 2013, 2014) which is to date the only multi-specific weed dynamics model that integrates the whole crop and soil management systems and their interactions with pedoclimatic conditions (Colbach, 2010).

2. Materials and methods

2.1. Seed movement model

The conceptual model to be tested on the field experiments is represented in Fig. 1. Tillage is assumed to mix soil and seeds, concentrating aggregates larger than 2 cm towards soil surface whereas weed seeds and fine earth congregate below. There is thus a seed-free layer whose thickness (x_0) depends on initial soil structure and water content as well as tillage type and depth. The less the tillage operation fragments the soil and the deeper the operation, the larger is x_0.

Weed seeds that were initially (i.e. just before the tillage operation) close to soil surface are relocated by tillage between x_0 and tillage depth $x_{\text{tillage depth}}$. Initially buried seeds tend to stay deeper. They are therefore relocated between $x_0 + a_0 \cdot x_{\text{initial depth}}$ and $x_{\text{tillage depth}}$, where a_0 is the effect of initial seed depth on the shallowest possible burial depth after tillage.

In case of vigorous inverting operations (such as those performed by disc harrows) which are better at moving initially buried seeds towards soil surface, seeds are buried less deeply and are thus relocated between $x_0 + a_0 \cdot x_{\text{initial depth}}$ and $x_{\text{tillage depth}} - a_f \cdot x_{\text{initial depth}}$, where a_f is the effect of tillage tool (vigorously investing vs. other) on maximum burial depth, depending on initial seed depth.

These processes are translated into equations to predict the cumulated proportion of seeds $p(x_{\text{final depth}})$ as a function of the seed depth $x_{\text{final depth}}$ after tillage (Table 1A).

2.2. Field trial

To test the validity of the previous seed movement concept, a field trial was set in 2006 at the INRA experimental station of Dijon-Époisses, France (47°20′ N, 5°2′ E, 220 m asl) to evaluate the proposed model. The trial was on an eutric cambisol (FAO).

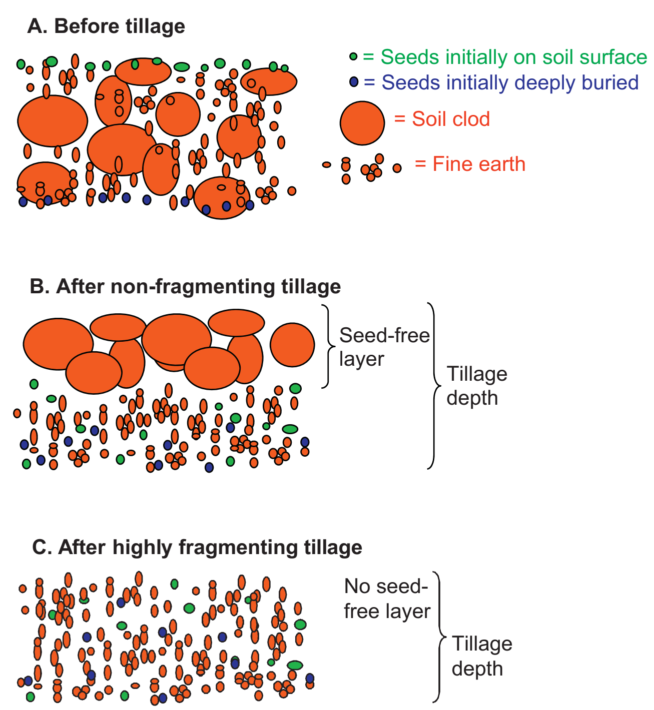

Fig. 1. Proposed conceptual model for weed seed movements during tillage. Tillage concentrates soil aggregates mostly towards soil surface whereas weed seeds and fine earth are concentrated below. Seeds initially on soil surface are distributed over a larger layer than initially buried seeds which remain deeper (Nathalie Colbach 2013©).