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Separating the confounding effects of farming practices on weeds and winter wheat production using path modelling

Maude Quinio[a], Mélanie De Waele[a], Fabrice Dessaint[a], Luc Biju-Duval[a], Marc Buthiot[a], Emilie Cadet[a], Ann K. Bybee-Finley[b], Jean-Philippe Guillemin[a], Stéphane Cordeau[a,b,*]

[a] Agroécologie, AgroSup Dijon, INRA, Univ. Bourgogne Franche-Comté, F-21000 Dijon, France
[b] Cornell University, Soil and Crop Sciences Section, Ithaca, NY 14853, USA

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ABSTRACT

Optimal crop yield can be achieved directly by optimizing farming practices to increase crop growth and indirectly by optimizing pest management to decrease pest pressure. The aim of this study was to quantify the indirect effect of farming practices on yield through a change of the weed pressure and, thereby, disentangle the effect of farming practices on yield and weeds. Between 2006 and 2012 in Burgundy, France, 152 winter wheat fields were surveyed for weeds and farmers were interviewed about their farming practices and yields. Data were analysed using partial least square path modelling (PLS-PM). A path model that related farming intensity (fallow management, sowing, chemical pest control and fertilization), crop productivity (yield), and weed pressure was designed and validated. It was then used to assess the relationships between the identified variables (β path coefficients) and compare groups of fields varying in, the preceding crop, herbicide use and weed pressure in the field. Farming intensity had a positive effect on crop productivity (β = 0.32). Weed pressure negatively impacted crop productivity (β = −0.12). Farming intensity decreased weed pressure and had a sufficiently negative effect on weeds (β = −0.19) to counteract the negative impact of weeds on crop productivity. Therefore, the indirect effect of farming intensity on crop productivity through a change of weed pressure was positive and accounted for 7% of the total (direct + indirect) effect of farming intensity on crop productivity. The indirect effect of farming intensity on crop productivity varied by preceding crop (3.6% and 23% with a winter and spring/summer preceding crop, respectively) and herbicide use (14.1% and 2.1% when herbicide use was less and more than the regional reference, respectively) and weed pressure (0.5% and 2.6% when the total weed abundance after weeding was less and more than 2 individuals m^{-2}, respectively). From the path model, we quantified the direct and indirect effects of farming intensity on crop productivity to show that effective weed management can sustain crop production in cropping systems with reduced herbicide use.

1. Introduction

In France, herbicides represented 43.8% of total pesticides used in 2014 (European Crop protection http://www.ecpa.eu/). Reducing the reliance of cropping systems on herbicide use is promoted throughout Europe (*e.g.*, EU legislation and French ECOPHYTO plan) since the negative impacts of intensive agriculture on environment and health have been highlighted (Soule et al., 1990; Stoate et al., 2009). Farmers must now work to improve both their economic and environmental performance. Weed management represents one of the major challenges for sustainable agriculture (Petit et al., 2015) because weeds represent a major biotic constraint (Oerke, 2006) and because weed management practices continue to rely heavily on the use of synthetic herbicides (Chauvel et al., 2012).

A large number of studies have assessed the overall impact of a cropping system (*e.g.*, crop management and rotation) on crop yields and weeds (see *e.g.* Chikowo et al., 2009). Most farming practices that target crop growth also impact weed communities, and as

Abbreviations: FTFI, Fungicide Treatment Frequency Index; FRAC, Fungicide Resistance Action Committee; GoF, goodness-of-fit; HTFI, Herbicide Treatment Frequency Index; HRAC, Herbicide Resistance Action Committee; ITFI, Insecticide Treatment Frequency Index; IRAC, Insecticide Resistance Action Committee; IWM, integrated weed management; LV, latent variable; MV, manifest variable; TTFI, Total Treatment Frequency Index.

* Correspondence to: INRA, UMR1347 Agroécologie, 17 rue Sully, BP 86510, F-21065 Dijon cedex, France.
E-mail address: stephane.cordeau@inra.fr (S. Cordeau).

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such, likely affect crop productivity in an indirect manner as well. For example, tillage can improve soil structure to favour crop seed emergence, root establishment and rapid early growth (Mead and Chan, 1988). However, tillage stimulates weed seed germination (Bàrberi and Lo Cascio, 2001) which leads to weed emergence in the crop and to competition for resources. Irrigation and fertilization aim to reduce the limiting effect of water and nutrients on crop growth (Gajri et al., 1993). However, a higher availability of these resources tends to increase the weed-crop competition and promote the growth of the most nitrophile weed species (Moreau et al., 2014).

Few studies have attempted to disentangle the effects of particular farming practices on weeds and yield. Rasmussen (1991) used models to separate the weed-killing effect (positive) and crop-covering effect (negative) of harrowing on crop yield. Other studies have focused on the overall effect of cropping systems on weeds and yields. Chikowo et al. (2009) demonstrated that integrated weed management (IWM) systems could reduce herbicide reliance, maintain low weed pressure, and sustain productivity. However, these studies did not show causal links between the three separate conclusions. No study has ever quantified the direct effect of farming practices on yield and the indirect effect of these farming practices on yield as caused by a change in weed pressure.

The goal of this study was to quantify the direct and indirect (due to change in weed pressure) effects of farming practices on crop productivity (*i.e.* yield), in conventional winter wheat (*Triticum aestivum* L.). Winter wheat was chosen as it is the most widely cultivated crop in France and Europe. Crop management, crop yields, and weed communities were surveyed in 152 fields over the 2006–2012 period in Burgundy, eastern France and analysed with partial least square path modelling (PLS-PM). The study consisted of three steps: (i) building a PLS-PM model that linked farming practices, weed communities' descriptors, and crop yield; (ii) validating the PLS-PM model and quantifying the relationships between variables; (iii) using the model to compare groups of fields with various cropping systems and weed pressures. We hypothesized that (1) the indirect effect of farming intensity on productivity through changes in weed pressure would be positive, that is, crop productivity would increase as farming intensity reduced weed pressure and (2) these direct and indirect effects vary by crop and weed management, such as the preceding crop in rotation or the intensity of herbicide use.

2. Materials and methods

The study was conducted in the Fénay study area located near Dijon in eastern France (47°13′N, 5°03′E) on 890 ha. We assumed homogenous soil features of clay and clay loam and continental climate conditions (744 mm of average precipitation per year) across the area. The area is mostly cultivated with grains (42% winter cereals and 13% oilseed rape) in rotation with spring and summer crops (*e.g.* spring barley and sunflower). Over the 2006–2012 period, 152 site-years planted with winter wheat were examined (Fig. 1).

2.1. Data collection

2.1.1. Weed surveys

All surveys took place from March to early May (with half of the surveys occurring during the two first weeks of March), after all herbicide applications. No mechanical weeding was performed in any of the site-years. Thus, we observed the weed communities remaining after chemical weed control.

A walking survey was conducted in each field through a 2000 m^2 (40 m × 50 m) area to determine weed communities according to the methodology described by Fried et al. (2009). The survey areas

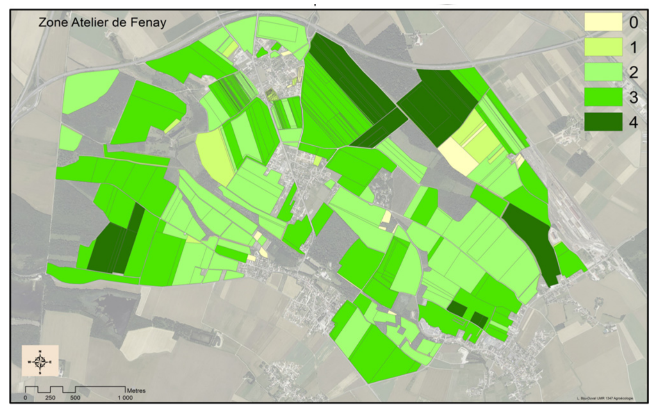

Fig 1. Frequency of winter wheat crops per field (number of occurrence within the 2006–2012 period) using a color gradient in the Fénay area of Burgundy in eastern France.

were located in the core of each field at least 20 m from the field boundary to avoid confounding effects of species spreading from field edges (Cordeau et al., 2012). The weed species were listed and their density was visually estimated following the methodology of Fried et al. (2009) with 6 classes (one individual in the 2000 m^2 area, <1 individual m^{-2}, 1–2, 3–20, 21–50, and 51–100 individuals m^{-2}). The total weed abundance was computed using the centre of each density class (0.0005, 0.5, 1.5, 11.5, 35.5, and 75.5 individuals m^{-2}, respectively). Species richness (number of species), total weed abundance (individuals m^{-2}), and the Shannon Diversity Index (H) were computed for each site-year (Table 1). The Shannon Diversity Index was computed as $H = -\sum p_i \ln p_i$, where p_i is the proportion of individuals belonging to the ith species.

2.1.2. Farmers interviews

Farmer interviews were conducted each year between 2006 and 2012 to collect data on yield and farming practices implemented in each field for that year. Farming practices were organised into four groups: *fallow management*, *sowing*, *chemical pest control*, and *fertilization* (Table 1). For each farming operation, the date and the number of passes were recorded. When implemented, ploughing and loosening generally consisted of 20 cm depth inversion tillage and 40-cm depth non-inversion tillage, respectively. We defined shallow tillage as the slightly tillage implemented for stubble management, stale seedbed and seedbed preparation. Pesticide use information included the commercial product and the dose at which it was sprayed so that the treatment frequency index (TFI) as detailed by Gravesen (2003) could be computed. TFI is commonly used in Europe to assess the reliance of cropping systems on pesticides (OECD, 2001) and is calculated for each pesticide as the number of full doses applied per hectare and per crop season. We identified the mode of action of each pesticide with the Herbicide Resistance Action Committee (HRAC, www.hracglobal.com), the Fungicide Resistance Action Committee (FRAC, www.frac.info), and the Insecticide Resistance Action Committee (IRAC, www.irac-online.org), and then computed the number of modes of actions applied per crop season (Table 1).

2.2. Statistical analysis

Partial least square path modelling (PLS-PM) was used to model the relationships between farming intensity, crop productivity, and weed pressure. All of the analyses were performed with the R 3.1.2 software (R Core Team, 2015), using the plspm package (Sanchez and Trinchera, 2012). PLS-PM is a method most commonly used in social sciences, although it has been used increasingly in ecological studies (Majdi et al., 2014; Fu et al., 2015; Puech et al., 2015).