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Assessment of functional forms of crop yield loss models of invasive plant species applied in decision support tools and bioeconomic modelling

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ABSTRACT

Objectives: Decision support tools (DSTs) for invasive species management have had limited success in producing convincing results and meeting users' expectations. The problems could be linked to the functional form of model which represents the dynamic relationship between the invasive species and crop yield loss in the DSTs. The objectives of this study were: a) to compile and review the models tested on field experiments and applied to DSTs; and b) to do an empirical evaluation of some popular models and alternatives.

Design and methods: This study surveyed the literature and documented strengths and weaknesses of the functional forms of yield loss models. Some widely used models (linear, relative yield and hyperbolic models) and two potentially useful models (the double-scaled and density-scaled models) were evaluated for a wide range of weed densities, maximum potential yield loss and maximum yield loss per weed.

Results: Popular functional forms include hyperbolic, sigmoid, linear, quadratic and inverse models. Many basic models were modified to account for the effect of important factors (weather, tillage and growth stage of crop at weed emergence) influencing weed–crop interaction and to improve prediction accuracy. This limited their applicability for use in DSTs as they became less generalized in nature and often were applicable to a much narrower range of conditions than would be encountered in the use of DSTs. These factors' effects could be better accounted by using other techniques.

Among the model empirically assessed, the linear model is a very simple model which appears to work well at sparse weed densities, but it produces unrealistic behaviour at high densities. The relative-yield model exhibits expected behaviour at high densities and high levels of maximum yield loss per weed but probably underestimates yield loss at low to intermediate densities. The hyperbolic model demonstrated reasonable behaviour at lower weed densities, but produced biologically unreasonable behaviour at low rates of loss per weed and high yield loss at the maximum weed density. The density-scaled model is not sensitive to the yield loss at maximum weed density in terms of the number of weeds that will produce a certain proportion of that maximum yield loss. The double-scaled model appeared to produce more robust estimates of the impact of weeds under a wide range of conditions.

Conclusions: Previously tested functional forms exhibit problems for use in DSTs for crop yield loss modelling. Of the models evaluated, the double-scaled model exhibits desirable qualitative behaviour under most circumstances.

1. Introduction

Appropriate level of management of weed and other invasive species would significantly increase crop yield and other economic benefit to farmers. Current management decisions determine the spread, damage intensity and economic impact of invasive species in and beyond the treated area, both now and in the future (Heikkilä, 2011). The complex relationships between incursion response and management outcomes make it inherently risky and costly to determine the appropriate levels of protection without a sound evidence base. Decision support tools (DSTs) are often used to assist decision-makers in analyzing complex problems in a structured way enabling critical economic and ecological thresholds to be identified, and making informed decisions for the

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appropriate level of protection (Wilkerson et al., 2002). However, studies show that DSTs in the biosecurity field have had limited success in producing convincing results and meeting users' expectations (Wilkerson et al., 2002; Zimdahl, 2004). Critical problems associated with the tools include: large differences between estimated and observed values; poor representation of biophysical phenomena; unrealistic results at extreme values of input; and lack of simple and interpretable parameters used within the DSTs (Holst, 2005; Wilkerson et al., 2002). One of the most critical factors determining the performance of DSTs is the functional form of mathematical model which abstractly represents the relationship between invasive species population and crop yield loss. Researchers have tested and recommended many functional forms (Cousens, 1985; Doyle, 1991; Edalat et al., 2011; Holst, 2005; Zimdahl, 2004). However, users have experienced problems when applying the models and the information derived from them (Wilkerson et al., 2002).

The functional relationship between the invasive species and the crop, and the subsequent effect on economic losses is very complex. It varies with the nature of population distribution (i.e. irregular, sparse, clustered or extensive), degree of amensalism or competitiveness (i.e. high, medium or low), and the type of damage (i.e. competitive, predatory, inhibitive, toxic and contaminative). It would be prohibitively expensive and practically impossible to derive the functional form from field tests for each combination of crop and invasive species in all environments in which these biophysical interactions are of interest (Wilkerson et al., 2002). Typically, experimental studies have evaluated yield loss of cereal crops and common weed species and various functional forms have been applied to describe the results. Most tests focused on agronomic aspects, and gave little attention to ecological aspects and other requirements for bioeconomic modelling such as performances at extreme densities (Wilkerson et al., 2002; Zimdahl, 2004). Many of the functional forms applied or recommended have limitations in their use (Cousens, 1985; Doyle, 1991; Edalat et al., 2011; Holst, 2005; Wilkerson et al., 2002; Zimdahl, 2004) but the issues have not been compiled, reviewed and published in accessible literature. As a result, DST developers and bioeconomic modellers have experienced problems in choosing an appropriate functional form to use.

The purpose of this study was to document application problems and determine the robust functional forms for estimating crop yield loss by weed invasion. The purpose is achieved by working on two components: a) to review functional forms tested in field and applied to DSTs including bioeconomic modelling; and b) to carry out an empirical evaluation of some popular models as well as potential models to assess crop yield loss. We collated available models and evaluated their utility. The rationale for using various functional forms is discussed and the issues that should be considered when selecting a particular model are outlined. Then, the robustness of some simple functional forms of crop yield loss models is analyzed through some simple modelling of their behaviour under a range of conditions. The applicability of different functional forms is discussed.

Table 1
Definition of terms used to describe the yield loss models.

The term	Definition of the term
I	Marginal yield loss per weed as its density approaches zero (%)
A	Maximum possible yield loss (%)
D	Density of weed
Y	Crop yield of weed infested field
Y_L	Yield loss (%)
Y_m	Weed-free yield
βc	Intra-specific competition factor for crop plant
βi	Competition factor of weed on crop
α	A constant term of the model
μ	A half saturation constant factor in the Odom et al. (2005) model
a	Density at which yield is a half of its potential maximum in the RIM model (Pannell et al., 2004)
q	Relative damage coefficient of weed in crop index model
L_w	Leaf area index of weed
i	*i*th species in multiple weed management models
Rd	Relative weed density which can be calculated as the weed density presence in the field divided by maximum potential density at maximum potential yield loss level
Γ	A damage function parameter – interaction outcomes of weed free yield and herbicide effect in the Ghadim et al. (1991) model
k	Density dependent yield function in the Andujar and Quintanilla (1993) model
τ	The factor for yield damage other than the yield of main crop in the Kaye-Blake et al. (2010) model
ω	A factor for wastage of pasture yield due to bristle or other barrier of weed for grazing
Z	A factor of crop yield damage by weed infestation
Deq_t	Summation of density equivalent weight of all weed species in multiple species model
Po	Standard crop density in the RIM model
P1	Crop density in weed infested condition in the RIM model
σ	A constant factor for yield variability adjustment in the logistic model by Lybecker et al. (1991)
$\ddot{I}$	Per weed average percentage of yield loss which was calculated on total yield of a unit production area.
β	Slope parameter in the logistic model by Vitta and Satorre (1999)
T	Thermal time in degree day (°C d) in the Vitta and Satorre (1999) model
r	Intrinsic biomass growth rate of species
δ	A curvature measure that determines the point at which yield begins to decline at a decreasing rate (i.e. the upper curve of the sigmoid) in the Swinton and Lyford (1996) model
TCL	Total competitive load in the Wilkerson et al. (2002) model
CL_i	Competitive load of species, ***i***, of test interest
Θ	Scaling parameter for the most competitive species in the Wilkerson (2002) model
$b_{\dot{r}}/a_{\dot{r}}$	An index of the competitive ability of the reference species, $\boldsymbol{\ddot{I}}$
b_i/a_i	An index of the competitive ability of the test species, ***i***, in the Wilkerson (2002) model

2. Method

This study has two parts: a review of functional forms and an empirical analysis of some of these forms.

2.1. Review of crop loss models

The first part of the study involved a desktop review of literature and other sources of experts' information. We searched the literature to collate the functional forms of yield loss models that have been experimentally tested and applied by DST developers. The following data sources were searched: ScienceDirect (http://www.sciencedirect.com/), Wiley (http://www.wiley.com/go/databases), ProQuest (http://www.proquest.com), Springer (http://www.springer.com) and Google databases. The key words used for searching the literature included "invasive species", "yield loss model", "yield loss functional form", "yield damage function", and "bioeconomic model". Some additional articles were identified from the references in the primary source articles. Papers published since 1985 were examined: Cousens (1985) reviewed 18 models used in experimental studies, as listed in Appendix Table A1. Previous studies used different notations when referring to the same term, so for ease of presentation and understanding, this study standardizes the terms used – see Table 1.

2.2. Evaluation of behaviour of selected models

From the plethora of functional forms present in the literature, we evaluated three commonly used in bioeconomic modelling studies (linear, hyperbolic and relative-yield loss models). Two "new" ones (the double-scaled and density-scaled models) were also evaluated. All were assessed against several DST requirements: qualitative agreement