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Estimating relative crop yield loss resulting from herbicide damage using crop ground cover or rated stunting, with maize and sethoxydim as a case study

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Summary

The research goal was to determine whether crop damage from herbicides measured early in the growing season soon after treatment could be used to estimate relative crop yield loss. Percentage stunting was rated visually and percentage crop ground cover (i.e. percentage of the ground surface covered by vegetation) was determined from video photographs taken 2–4 weeks after sethoxydim-susceptible maize (*Zea mays* L.) was sprayed with sethoxydim at various rates plus crop oil concentrate. Averaged over 3 years, relative percentage maize yield was a negative sigmoidal function of relative sethoxydim rates from 0.065× to 0.5×, where the 1× rate was 420 g a.i. ha^{-1} ($r^2 = 0.80$). Relative maize yield was positively linearly related to percentage crop ground cover and negatively linearly related to rated percentage stunting averaged over 3 years. Linear regression models of relative maize yield vs. percentage maize ground cover explained only slightly more data variability ($r^2 = 0.86$) than did rated stunting ($r^2 = 0.82$) over 3 years. The advantages and disadvantages of rated stunting and crop ground cover as scientific measurements are discussed.

Introduction

Occasionally, herbicides damage crops and reduce harvest yield and/or quality. Yield losses caused by registered herbicides may be the result of misapplication (incorrect rates, timing, additives or pesticide mixtures or sequences; Salzman & Renner, 1992), treating unregistered susceptible cultivars (Moseley *et al.*, 1993) or stressful environmental conditions that reduce crop tolerance to herbicides. Unregistered herbicides may reduce yield from misapplication, herbicide drift from nearby crops (Weidenhamer *et al.*, 1989) or herbicide residue carry-over after treating rotational crops (Wax *et al.*, 1969; Frank *et al.*, 1983).

At present, almost all quantitative field research on herbicide damage to crops relates yield loss only to herbicide application rate (i.e. dose–response or field bioassays), usually using regression analysis (Streibig & Kudsk, 1993). Other measured variables, such as height or fresh weight, are usually related only to herbicide application rate. There are extremely few published examples in which initial early damage from herbicides measured soon after treatment has been used as an independent variable itself, instead of herbicide rate, to estimate relative yield loss. No examples were found for maize in the refereed scientific literature, and a very limited number were found for other crop and herbicide combinations. For example, in a study of simulated drift damage, percentage visual injury measured 2 weeks after treatment was linearly related to yield of buckwheat (*Fagopyrum esculentum* Moench), field pea

(*Pisum sativum* L.), lentil (*Lens culinaris* Medic.) and sunflower (*Helianthus annuus* L.) treated with a mixture of trifensulfuron plus tribenuron (Wall, 1994).

The research goal was to compare how well relative crop yield loss at harvest could be estimated from two measures of early herbicide damage (e.g. crop ground cover and visually rated stunting measured soon after herbicide treatment) compared with herbicide rate, the usual independent variable. Although sethoxydim-tolerant maize cultivars are now available commercially, sethoxydim damage to maize was used as a model system, because it is well documented that this herbicide reduces the yield of susceptible maize cultivars in a dose-dependent fashion (Frank *et al.*, 1983; Chernicky & Slife, 1986; Chernicky *et al.*, 1989; Smart *et al.*, 1993)

Materials and methods

Treatments

From 1993 to 1995, the treatments (i.e. sethoxydim rates) were arranged in a randomized complete block experimental design with three or four replicates, depending upon available land. In 1994 and 1995, the treatments included an untreated control and various rates (0.065×, 0.12×, 0.25×, 0.35× and 0.5×) of sethoxydim, where the 1× rate was 420 g a.i. ha^{-1}, the United States Environmental Protection Agency registered rate for weed control in soyabeans [*Glycine max* (L.) Merr.]. In 1993, a 0.75× rate replaced the 0.35× rate. Maize was treated at the V1 stage (early whorl stage with the collar of the fourth leaf visible and the nodal roots developing) and was 49 (± 7) cm (mean ± standard deviation), 50 (± 6) cm and 51 (± 9) cm tall in 1993, 1994 and 1995 respectively. Plots measured 3 m by 9.1 m.

Sethoxydim (Poast EC, 146 g a.i. L^{-1}, BASF Corp.) was applied with a bicycle wheel sprayer operated at 4.8 km h^{-1}, 24, 19 and 15 days after maize emergence in 1993, 1994 and 1995 respectively (Table 1). Spray volumes of 123–125 L ha^{-1} were applied with Teejet 8001 flat fan nozzles (Spraying Systems, Wheaton, IL, USA) at 210 kPa each year. Crop oil concentrate was added at 1% of the spray volume. All plots were weeded by close mowing with a plastic cord mower, hoeing and hand pulling, as necessary, so that sethoxydim effects on yield would not be confounded by weed competition (Table 1).

Agronomic practices

Experiments were repeated from 1993 to 1995 on the Bradford Experimental Farm of the University of Missouri near Columbia (38°53′N, 92°12′W, 883 m altitude). The soil was a Mexico silt loam (fine, montmorillonitic, mesic Udollic Ochraqualfs) with 18–20% sand, 46–48% silt, 34% clay, 2.7–3.2% organic matter, cation exchange capacity of 13.2–20.5 meg 100 g^{-1} and pH of 5.5–5.7. Field operation dates for treatments and measurements are summarized for each year (Table 1). Weather data were collected at the Bradford Farm in 1993 and 1994, but data from Sanborn Experimental Field Station in Columbia were substituted in 1995 because of equipment automation failure at the Bradford Farm.

The experiment was repeated on adjacent sites, which were in a maize–soyabean rotation. In spring 1993, the site was disk-ploughed followed by tandem disking for seedbed preparation. In the springs of 1994 and 1995, the site was chisel-ploughed and field-cultivated for seedbed preparation (Table 1). Maize was fertilized with nitrogen, phosphorus and potassium for a yield goal of 7400 kg ha^{-1} each year, based on soil tests and recommendations of the University of Missouri soil testing laboratory. Fertilizers were broadcast before planting and were incorporated by field cultivation for seedbed preparation. Fertilizer (N:P:K) was applied at 110:80:70 kg ha^{-1} in 1992, 140:20:20 kg ha^{-1} in 1993 and 130:0:0 kg ha^{-1} in 1995.

Each year, maize seeds were planted 1.3–1.9 cm deep at 74 000–78 000 seeds ha^{-1} in 76-cm rows, with a four-row John Deere Maximerg maize planter (Des Moines, IA, USA) (Table 1). Although experimental and regional planting started earlier in 1995 than in 1993 or 1994, rainfall delayed the completion of planting in 1995 compared with the two previous years (Anonymous, 1993, 1994, 1995). The soil was rotary-hoed in 1993 to break a surface crust that restricted maize emergence. Maize emerged about 8, 6 and 7 days after planting in 1993, 1994 and 1995 respectively. Maize was sprayed with chlorpyrifos (Lorsban 4E, 394 g a.i. L^{-1}, Dow Elanco Corp.) for cutworm (*Euxoa* spp.) control

Table 1. Dates of field operations and measurements

Field operation or measurement	1993	1994	1995
Primary tillage			
Chisel-ploughed	–	23/10/93	4/4/94
Mouldboard-ploughed	12/5/93	–	–
Fertilize plots with nitrogen, phosphorus and potassium	17/5/93	11/5/94	14/6/95
Spring seedbed preparation and broadcast fertilizer incorporation			
Disk-ploughed	17/5/93	–	–
Field-cultivated	–	18/5/94	15/6/95
Maize planted	17/5/93	19/5/94	19/6/95
Maize emergence first observed	25/5/93	25/5/94	26/6/95
Maize rotary-hoed	26/5/93	–	–
Maize treated with insecticide	–	5/5/94	–
Started hand-hoeing/weeding maize plots	2/6/93	13–15/6/94	13/7/95
Herbicides applied to maize	17/6/93	13/6/94	10/7/95
Maize stand determined	10/6/93	10/6/94	30/6/95
Video photographs of maize ground cover	24/6/93	27/6/94	24/7/95
Visually rated herbicide maize stunting	12/7/93	28/6/94	24/7/95
Harvested maize	26/10/93	21/10/94	9/11/95

in 1994, based on University of Missouri integrated pest management guidelines.

Measurements

Maize damage (rated stunting) was evaluated visually using a rating system from 0% (no stunting) to 100% (completely killed). The same individual rated stunting over time in order to minimize between-observer error.

Percentage maize ground cover was measured from video photographs (Table 1). Video photographs were taken with a RC-570 still video camera (Cannon USA, Lake Success, NY, USA) at 7, 14 and 14 days after sethoxydim treatment in 1993, 1994 and 1995, respectively, as the weather allowed (Fig. 1). Video photographs were taken from a height of 194, 190 and 164 cm above the soil surface in 1993, 1994 and 1995 respectively. Video photographs were calibrated using a 30 cm by 30 cm orange metal plate placed on the soil surface so that each photograph corresponded to 1.6, 1.5 and 1.1 m^2 at the soil surface in 1993, 1994 and 1995 respectively. Video photographs were digitized using a SV-PC Digitizer still video board (Cannon USA) and saved as TARGA files for import into Sigma Scan video image analysis software version 1 (Jandel Scientific, San Rafael, CA, USA). Maize foliage was traced manually and quantified using the software, and crop ground cover pixels were expressed as a percentage of total pixels per video photograph. Averages of four separate photographs per plot are presented. Calculation of cover precision has been presented elsewhere (Da Silva *et al.*, 1986).

Maize seeds were harvested from the two centre rows in an area measuring 1.5 m by 8.4 m with an Allis Chalmers Gleaner model III combine harvester, and yields were reported after adjustment to 15.5% moisture content (Table 1).

Statistical analysis

Maize yields (kg ha^{-1}) were separately subjected to linear and non-linear regression analysis vs. three independent variables: sethoxydim rate (normalized to the 1× rate), visually evaluated rated stunting (%) and maize ground cover (%) measured from video photographs. Maize yield data were normalized (i.e. expressed as a percentage of the yield for untreated control plots) before regression analysis each year to minimize year-to-year variation caused by differences in maize yield potential among years resulting from factors other than herbicide stunting. Multiple linear regression analysis was also conducted with either rated stunting or ground cover, and three dummy variables were created to test year-to-year variation. Averages for 3 years are presented.

Results and discussion

Relative yield loss estimates using percentage crop ground cover and rated stunting

Relative maize yield was a negative sigmoidal function of relative sethoxydim rate each year

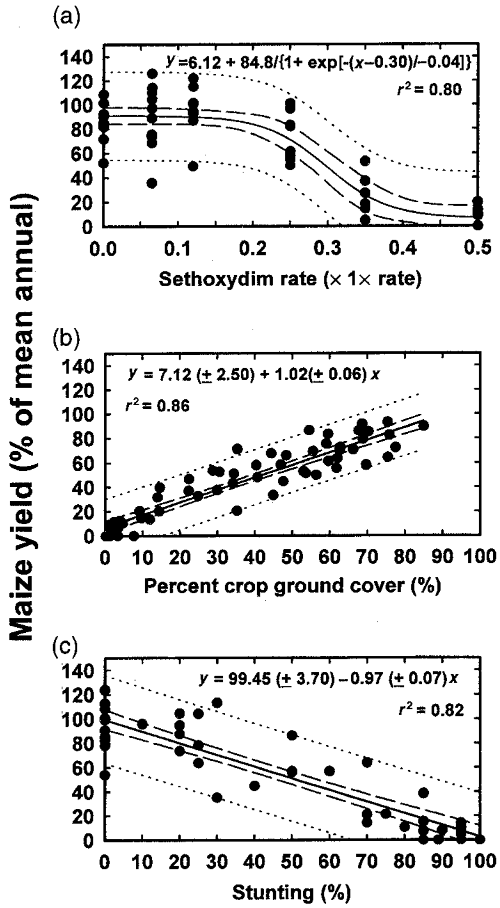

Fig. 1. Relative maize yield (expressed as a percentage of the mean annual yield) vs. relative herbicide rate (top), maize percentage ground cover (middle) and rated maize percentage stunting (bottom) averaged from 1993 to 1995. Observations (solid circles), fitted regression equations (solid line), 95% confidence intervals (dashed line) and 95% prediction intervals (dotted line) are presented. Equations are presented with coefficients (± standard errors).

(unpubl. data) and averaged over 3 years (Fig. 1), as expected for herbicide dose–response relationships (Streibig & Kudsk, 1993). Nevertheless, a linear function described the relationship almost as well as a sigmoidal model, presumably because of data variability (unpubl. data).

Relative maize yield was a positive linear function of percentage maize ground cover and a negative linear function of visually rated stunting averaged over 3 years (Fig. 1). Percentage maize ground cover explained slightly more regression model variability for relative maize yield ($r^2 = 0.86$) than did either relative herbicide rate ($r^2 = 0.80$) or rated stunting ($r^2 = 0.82$). Confidence and prediction intervals for the relationship between relative maize yield and percentage ground cover were also smaller than for rated stunting. Thus, percentage maize ground cover measured soon after treatment had slightly greater precision for estimating relative maize yield loss than rated stunting. Nevertheless, it is remarkable that rated stunting estimated relative yield loss as well as it did. Maize response to sethoxydim was relatively insensitive to relatively great differences in rainfall distribution and amounts from year to year (Fig. 2).

Although all three independent variables described 80% or more regression model variability over 3 years (Fig. 1), not all crops respond to herbicide damage so consistently over time as this (Donald, 1998). The reproducibility of such relationships over time probably depends upon the specific herbicide and crop combination under study. Perhaps such relationships are more consistent when herbicides reduce crop stand, herbicide damage is severe or when the crop has limited potential for yield component compensation. Sethoxydim severely reduced maize stand in a herbicide dose-dependent fashion (data not presented), and stand reductions are known to impact maize yield negatively (Duncan, 1975; Stoskopf, 1981). Herbicide translocation patterns and mode of action are probably also important. Poorly translocated phytotoxic contact herbicides only damage exposed sprayed foliage but allow later foliage growth and yield formation from shoot meristems. In contrast to this, herbicides such as sethoxydim, which translocate to shoot meristems and kill them (Chernicky & Slife, 1986), will prevent later leaf outgrowth, canopy development and yield component formation. These suggestions can only be tested by examining additional herbicide and crop combinations.

Comparison of rated stunting and ground cover as scientific measurements

The characteristics of rated stunting and ground cover as scientific measurements are compared in Table 2. Visually rated crop damage from herbicides, such as rated stunting, has been widely reported in the weed science literature in the past (Camper, 1986). Although visually rated stunting is appealing because it can be cheaply, quickly and inexpensively estimated, all measurements relying solely on human vision share

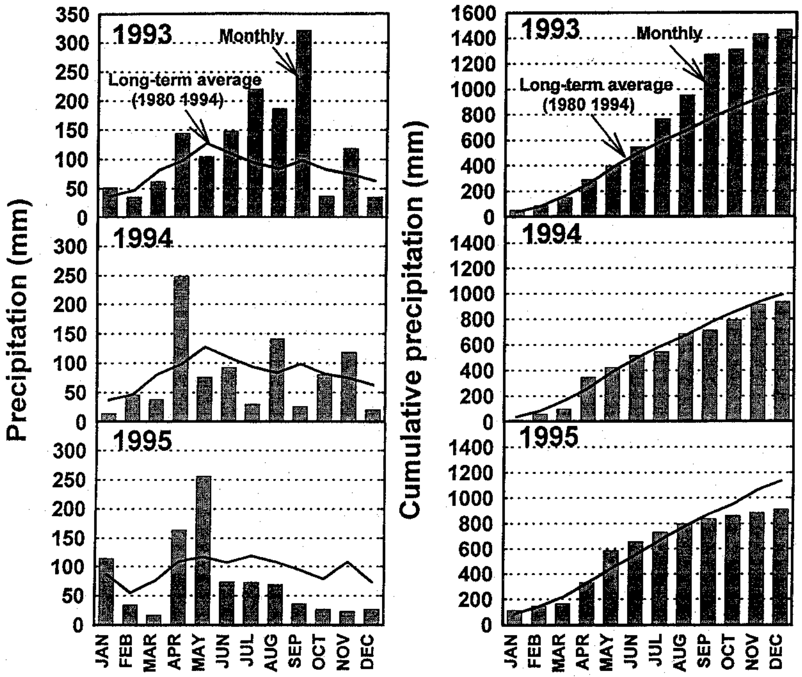

Fig. 2. Monthly precipitation (bars) and cumulative monthly precipitation (bars) in 1992–94 compared with long-term averages (1980–94) (open circles and lines respectively) at the Bradford Experimental Farm in 1993 and 1994 and Sanborn Field in 1995, near Columbia, MO, USA.

common limitations as scientific measurements (Spomer & Smith, 1988; Nilsson, 1995). Rated stunting has no absolute standard of comparison that does not change over time or between observers. Usually, rating is most precise at high and low values, but can be quite variable in the middle range of rating scales (Muir & McCune, 1987). Visual fatigue and the numbing effect of looking at plants over long periods make rating imprecise (Theunissen & Legutowska, 1992). By its very nature, visual rating is subjective, inconsistent and inaccurate over time (Spomer & Smith, 1988), rendering it unacceptable as a quantitative interval scale or ratio scale scientific measurement.

In the past, most reported crop ground cover has been estimated visually in the agronomic and weed science literature. When estimated visually, crop ground cover and rated stunting share the same limitations. But crop ground cover can also be measured more objectively (Bonham, 1989) from overhead photographs taken with either video, digital or chemical emulsion photography (Auld, 1978; Da Silva *et al.*, 1986). The advantages and disadvantages of ground cover as a scientific measurement are summarized in Table 2.

Suggestions for improving methodology

Year-to-year and site-to-site variation in planting date, herbicide treatment date in relation to growth stage, photograph collection date after treatment, crop cultivar and weather conditions are all likely to influence crop ground cover measurement reproducibility. These factors also influence canopy development rates, which in turn influence relative canopy measurements and rated stunting. In this research, percentage crop ground cover ranged between approximately 0.2% (i.e. most severely damaged) and 77.5% (i.e. untreated and undamaged) in 1993, between 1.5% and 85.0% in 1994 and between 2.9% and 75.9% in 1995 over all treatments. Apparently, the untreated maize canopy was somewhat more developed when measured in 1994 than in 1993 or 1995. In the future, variability might be reduced by making measurements when the untreated crop reaches a predetermined, standard percentage ground cover. Standard operating procedures could also be used for data collection and processing to improve reproducibility over several years among several observers (Donald & Schwartz, 1995).

Table 2. Characteristics of rated stunting and ground cover as scientific measurements

Measurement criterion	Measurement: Rated stunting	Measurement: Ground cover
Statistics		
Measurement unit	Visually estimated biomass loss compared with control plots (%)	Crop ground cover pixels as a percentage of total pixels in photograph (%)
Statistical scale	Ratio	Ratio
Measurement range	$0 \leq x \leq 100$	$0 \leq x \leq 100$
Statistical accuracy	Low	High
Measurement is objective (i.e. not highly dependent on the individual observer)	No	Yes
Observer experience and personal judgement are required	Yes	No
Measurements can be calibrated against absolute standards	No	Yes
Measurements are compared with changeable relative standards, such as control plots	Yes	No
Threshold for quantification	Observer dependent	Camera and sample size-dependent
Measurement system is stable over time	No	Yes
Measurement specificity (i.e. confirmed identity of measured object)	Yes	Yes
Statistical precision	Low	High
Precision over measured range	High at upper or lower extremes, but low in the middle range	Error increases as mean increases, sample size dependent
Reproducibility (= repeatability, consistency, reliability) over time (i.e. repeated measurement values of the same object are close to one another)	Low	High
Same observer gets reproducible values within narrow limits when repeatedly measuring the same object	No	Yes
Different observers get reproducible values within narrow limits when repeatedly measuring the same object	No	Yes
User requirements		
Cost		
Start-up costs for equipment	Low	High: video or digital camera, computer, CD-ROM or tape back-up and software
Training costs	Low	High
Licensing costs	No	Yes
Per sample cost	Low	High
Disposable supplies	Low	Low
Labour for field collection	Low	Low
Labour for laboratory analysis	Not applicable	High
Simplicity of field data collection	Yes	Yes
Ease of training	Yes	No
Ease of use in field	No	Yes
Simplicity in laboratory analysis	Not applicable	No
Ease of training	Not applicable	No
Ease of use in laboratory	Not applicable	Yes
Timeliness of measurement	High	High
Speed of field data collection	Fast	Fast
Weather or soil conditions may limit travel to make measurement	Yes	Yes
Speed of converting the measurements into information	Fast	Slow
Documentation creates a permanent record of raw data	No	Yes
Measurement is destructive	No	No
Raw data can be remeasured	No	Yes
Physical scale of measurement	Small plot	Sample within small plot
Scale can be increased to field scale	No, observer dependent	Yes, aerial photography and remote sensing
Measurement can be automated	No, observer dependent	Yes

As pointed out in the Introduction, most field studies documenting herbicide damage to crops simply relate yield loss to herbicide rate. When damage is caused by non-uniform drift or carry-over of herbicide residues, herbicide rate is variable across fields and is unknown. Consequently, after crop damage, herbicide rate cannot be used to guide crop management decisions, such as replanting, on commercial fields, although it is useful for research purposes.

If potential yield losses could be estimated from observed herbicide damage early in the growing season, rather than from herbicide rate, this information might help farmers to improve crop management decisions, such as replanting or taking legal action. However, this has not been attempted on a field scale. Because it relies on human observers, rated stunting also cannot be scaled up or automated from the research plot scale to entire fields. Because of its many flaws, rated stunting should be abandoned as a scientific measurement in its currently used format. Crop ground cover is one alternative to rated stunting for measuring crop damage. Ground cover may become less costly to measure in the future with technological advances in digital photography, remote sensing, image analysis software, combine-mounted yield monitors with global positioning systems and the use of geographical information systems. But scaling up and automating this research for field use will require additional effort.

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