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Estimated soybean (*Glycine max*) yield loss from herbicide damage using ground cover or rated stunting

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The primary goal of this research was to determine whether crop damage from herbicides measured soon after treatment could estimate relative crop yield loss. Two to 4 wk after spraying soybeans with an unregistered mixture of thifensulfuron plus sethoxydim at various rates plus crop oil concentrate, percent stunting was visually rated and percent projected ground cover of soybeans was determined from photographs. In each of 3 yr, relative percent soybean yield was a negative linear function of relative herbicide rate from 0.25× to 2× the registered (1×) rate. The 1× rate of thifensulfuron and sethoxydim was 17.5 and 420 g ai ha^{-1}, respectively. Relative soybean yield was also negatively related linearly to stunting but positively related linearly to soybean ground cover over 3 yr. Linear regression equation models of relative soybean yield versus percent soybean ground cover explained more model variability, more consistently ($R^2 \geq 0.60$ in two of 3 yr) than did either stunting ($R^2 \geq 0.60$ in one of 3 yr) or relative herbicide rate ($R^2 = 0.37$ to 0.48 over 3 yr). However, linear regression models for each independent variable differed from year to year and were related to differences in rainfall following treatment. Ways are suggested to increase regression model precision and between-year reproducibility.

Nomenclature: Sethoxydim; soybean, *Glycine max* (L.) Merr. 'Pioneer 9381.'

Key words: Image analysis, phytotoxicity, video photography, sethoxydim, thifensulfuron.

Registered or unregistered herbicides occasionally damage crops, delay and decrease crop growth, and reduce harvest yield and quality. Registered herbicides can damage and reduce yield following misapplication (inappropriate rates, incorrect timing, additives, or pesticide mixtures or sequences) (Salzman and Renner 1992), treatment of susceptible varieties (Moseley et al. 1993), or application under stressful environmental conditions that limit crop tolerance to herbicides that normally do not damage crops (Osborne et al. 1995). Herbicides that are not registered on some crops may also decrease the yield of those crops following herbicide drift from nearby fields (Weidenhamer et al. 1989) or herbicide residue carryover from previously treated rotational crops (Frank et al. 1983; Wax et al. 1969) as well as following misapplication.

Much qualitative and quantitative information on herbicide damage to crops has been published. Qualitative information includes photographs (Ladlie 1991) and descriptions of typical herbicide damage symptoms. Quantitative information includes dose–response studies in which visually rated crop damage, biomass, height, or yield are related to herbicide rate, usually using regression analysis (Streibig and Kudsk 1993). If potential yield losses could be estimated from observed herbicide damage early in the growing season, this information might help farmers improve crop management decisions (e.g., replant to the same or a different crop? sue the applicator, dealer, or manufacturer? etc.). Herbicide rate has not been used for this purpose because it is frequently unknown outside of formal field experiments, or it is too costly to measure following herbicide drift or carryover.

Visually estimated crop damage from herbicides has been related to yield loss. For example, injury symptoms caused by simulated dicamba drift were related to percent soybean yield loss (Weidenhamer et al. 1989). In another drift experiment, primisulfuron damage to soybeans measured soon after treatment (e.g., reduced height, leaf chlorosis, cupping, and necrosis) was correlated with percent yield loss (Bailey and Kapusta 1993). In a third drift study, percent visual injury measured 2 wk after treatment was linearly related to final yield for 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).

Crop ground cover can be measured more objectively and lends itself to automation more easily than visual estimation of crop damage. Crop projected ground cover has been measured from overhead photographs using either video or chemical emulsion photography (Auld 1978; Thomas et al. 1988). Weed projected ground cover also has been used to quantify weed damage from herbicides (Floyd and Anderson 1982; Riepma 1965). Advances in computer video or digital photography, photograph digitization, and image analysis make it possible to use crop ground cover to estimate crop damage from herbicides.

One goal of this research was to determine whether crop damage or phytotoxicity measured soon after herbicide treatment could be used to estimate relative crop yield loss at harvest. Another goal was to compare two measures of crop damage for this purpose: soybean ground cover from video photographs and visually rated stunting. A secondary goal of this research was to determine how consistently the test mixture thifensulfuron plus sethoxydim damaged soybeans and whether any differences in year-to-year damage could be related to observed weather conditions. Damage caused by this unregistered mixture was used only as a model sys-

Table 1. Dates of field operations and measurements.

Field operation or measurement	1992	1993	1994
Planted soybean with *Rhizobium inoculant*	May 7	May 17	May 19
Herbicides applied to soybean	Jun 12	Jun 17	Jun 13
Video photographs of herbicide damage taken for measuring soybean ground cover	Jun 23	Jun 24 Jul 12	Jun 27 Jul 5
Visually rated soybean stunting	Jun 23	Jul 12	Jul 11
Harvested soybean	Oct 14	Oct 25	Oct 6

tem, solely to determine whether crop ground cover measured using video photography had promise as an early measure of relative soybean yield loss.

Materials and Methods

Agronomic Practices

Experiments were repeated from 1992 to 1994 at the University of Missouri's Bradford Experimental Farm near Columbia (38°53′43.5″N, 92°12′37.9″W, 883 m altitude). The soil was a Mexico silt loam (fine, montmorillonitic, mesic Udollic Ochraqualfs) with 18 to 20% sand, 46 to 48% silt, 34% clay, 2.7 to 3.2% organic matter, cation exchange capacity of 13.2 to 20.5 meq (100 g)$^{-1}$, and pH 5.9 (1992) and 5.5 to 5.7 (1994). Field operation dates for treatments and measurements are summarized for each year (Table 1).

The site had been fallowed and untilled for at least 3 yr before starting the experiment. In spring 1992, the site was moldboard plowed followed by rototilling and field cultivation for seedbed preparation. The site was disced before field cultivation for seedbed preparation in 1993 and 1994. In 1993 and 1994, soybeans were planted on adjacent sites in rotation with corn (*Zea mays* L.). Soybeans were fertilized with phosphorous and potassium for a yield goal of 3,360, 2,690, and 2,690 kg ha^{-1} in 1992, 1993, and 1994, respectively, based on soil tests and recommendations of the University of Missouri soil testing lab. Fertilizers were broadcast before planting and incorporated by field cultivation for seedbed preparation. N- P_2O_5-K_20 were applied at 0-67-45 kg ha^{-1}, 0-56-90 kg ha^{-1}, and 0-40-34 kg ha^{-1} in 1992, 1993, and 1994, respectively.

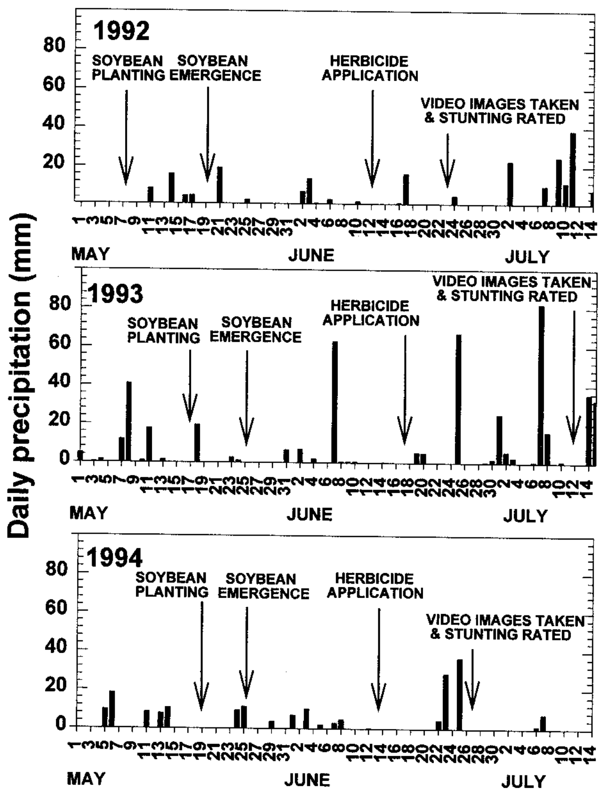

Figure 1. Daily precipitation graphed vs. time in 1992 to 1994. Dates of soybean planting, initial emergence, herbicide application, and early-season measurements are indicated by arrows.

Each year, *Rhizobium*-treated soybean seed was planted at 63,500 seeds ha^{-1} in 76-cm rows 1.3 to 1.9 cm deep with a 4-row planter (Table 1). Planting was about 2 wk later in 1993 and 1994 than in 1992 because of cool temperatures. The site was rotary hoed soon after planting in 1993 to break a surface crust that restricted crop emergence. Soybeans emerged 12, 8, and 6 d after planting in 1992, 1993, and 1994, respectively.

Soybeans were sprayed with acephate (*O,S*-dimethyl acetylphosphoramidothioate) to control bean leaf beetle [*Cerotoma trifurcata* (Foster)] in 1992 and with chlorpyrifos [*O*-diethyl-*O*-(3,5,6-trichloro-2-pyridinyl) phosphorothioate] for cutworms (*Euxoa* spp.) in 1994, based on University of Missouri integrated pest management guidelines. Dates of soybean planting, emergence, herbicide treatment, and video photography are graphed in relation to daily rainfall (Figure 1).

Herbicide Treatments

The treatments were an untreated check and thifensulfuron plus sethoxydim at various rates (0.25×, 0.5×, 0.75×, 1×, and 2×) where the 1× rates were 17.5 and 420 g ai ha^{-1}, respectively, according to the 1992 U.S. Environmental Protection Agency registration labels (Table 1). Crop oil concentrate was added at 1% of the spray volume. Postemergence thifensulfuron[1] plus sethoxydim plus crop oil concentrate is not registered by the U.S. Environmental Protection Agency on soybean because this mixture can severely injure soybean. Herbicides were applied 24, 23, and 19 d after soybean emergence in 1992, 1993, and 1994, respectively, with a bicycle wheel sprayer operated at 4.8 km h^{-1} (Table 1). Spray volumes of 110, 125, and 123 L ha^{-1} were applied with flat fan nozzles[2] at 276, 210, and 210 kPa in 1992, 1993, and 1994, respectively. Soybeans were sprayed at the V2 growth stage and were 10 to 15 cm tall in 1992 and 13 to 17 cm tall in 1993. In 1994 they were at the V3 growth stage and were 19 to 20 cm tall when treated. Treatments were arranged in a randomized complete block ex-

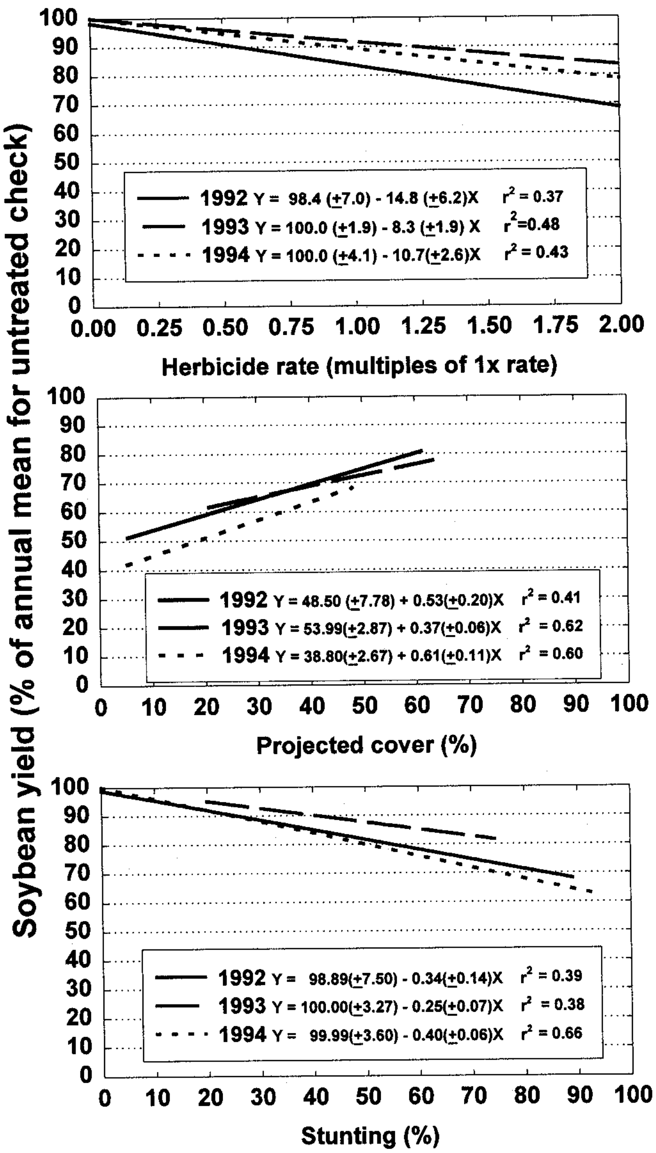

FIGURE 2. Relative soybean yield vs. relative herbicide rate, soybean ground cover, and soybean stunting in 1992 to 1994. Fitted regression line, regression equations, and R^2 are presented for each year. Untreated soybean yield was estimated to be 2,780 kg ha^{-1} in 1992, 2,650 kg ha^{-1} in 1993, and 2,100 kg ha^{-1} in 1994 by regression analysis for soybean yield as a function of relative herbicide rate (top panel).

perimental design with 3 to 4 blocks depending upon available land. Treated plots measured 3 by 9.1 m.

Weed escapes were controlled mechanically in all plots so that herbicide effects on yield were not confounded by weed competition. Weeds present before planting were controlled by seedbed preparation in spring. During the growing season, weed escapes following thifensulfuron plus sethoxydim treatment were controlled in a timely fashion by hand-pulling within rows and by close mowing with a plastic cord mower between rows followed by hoeing and hand-pulling weeds several times during the growing season.

Measurements

Crop stand was determined by counting plants in two 1.8-m lengths in the two center rows of each four-row plot. Crop stunting was visually rated from 0 (no damage or stunting compared to the untreated check) to 100% (killed). Soybean seed was harvested with a plot combine from the two center rows in an area measuring 1.5 by 8.4 m (Table 1). After seed cleaning, yields and moisture contents were measured, and net yields were adjusted to 13% moisture.

Soybean projected ground cover (% of the ground surface covered by vegetation [Bonham, 1989]) was measured from video photographs[3] taken soon after crop damage was rated (Table 1). Video photographs were taken 11, 25, and 22 d after herbicide treatment in 1992, 1993, and 1994, respectively, as weather permitted. Crop projected ground cover was averaged from four measurements per plot taken between the two center rows. Video photographs were taken at a height of 175 cm above the ground using a Xapshot video camera[8] in 1992, and at 140 cm using an RC-570 video camera[8] in 1993 and 1994. Video photographs were calibrated using a 45.5 by 45.5 cm quadrat placed on the ground in 1992 and a 30 by 30 cm orange metal plate in 1993 and 1994. In 1992, each photograph corresponded to 0.42 m^2 at the ground, and in 1993 and 1994, each photograph corresponded to 0.79 m^2. Video photographs were digitized[4] and saved as TARGA files for import into video image analysis software.[5] Projected ground cover of soybean foliage was measured manually in pixels and was expressed as a percent of all pixels per photograph. Methods for estimating precision and accuracy of cover measurements was presented (Thomas et al. 1988). Cover estimates were not corrected for height in this research.

Statistical Analysis

Each year, soybean yield (kg ha^{-1}) was subjected to linear regression analysis against three separate independent variables: herbicide rate (normalized to the 1× rate), stunting (%), and crop projected ground cover (%) (Kleinbaum and Kupper 1978). Then, soybean yield data were normalized (i.e., expressed as a percent of the estimated yield for untreated soybeans) as a way to reduce year-to-year variation in crop yield potential caused by factors other than herbicide damage, and linear regression analyses were conducted. Multiple linear regression analysis was also conducted with each independent variable and three dummy variables created to account for variability due to year. Multiple linear regression models incorporating dummy variables for years significantly improved model fit for estimating relative soybean yield loss from each independent variable (i.e., relative herbicide rate [i.e., rate expressed as a proportion of the 1× rate, soybean ground cover (%), and stunting (%)]) analyzed separately. By including dummy variables for year, R^2 values for multiple linear regression equations increased from 0.25 to 0.53 for relative soybean yield vs. relative herbicide rate, from 0.55 to 0.60 for relative soybean yield vs. ground cover, and from 0.058 to 0.447 for relative soybean yield vs. stunting. Because this analysis demonstrates that results differed between years, as expected based on weather differences between years, results will be presented separately by year.

Results and Discussion

Relative Yield Loss Estimates using Relative Herbicide Rate, Ground Cover, and Stunting

Relative soybean yield was a negative linear function of relative herbicide rate all 3 yr (Figure 2). However, relative herbicide rate explained only 37 to 48% of model variability (R^2) for relative soybean yield, depending on year. Relative soybean yield was also a negative linear function of stunting, although stunting explained 60% or more regression model variability in only one of 3 yr (Figure 2). In contrast, relative soybean yield was a positive linear function of ground cover. Soybean ground cover explained 60% or more model variability in 2 of 3 yr. Consequently, ground cover described greater amounts of model equation variability, more consistently, than did either relative herbicide rate or stunting. Nevertheless, different linear regression equations were required to model relative soybean yield from year to year for all three independent variables.

Year-to-Year Variation in Regression Models

Relative soybean yield was more severely decreased, ground cover was lower, and stunting was more severe after thifensulfuron plus sethoxydim treatment in 1992 and 1994 than in 1993 (Figure 2). In 1993, soybean leaves that were sprayed became severely discolored and damaged. Subsequent new leaf growth was normal, and plants eventually outgrew initial damage at most rates. After treatment in 1992 and 1994, shoot growth was slower and mature canopy cover never matched the untreated plants.

Because maximum and minimum daily temperatures shortly before and after herbicide application were similar in all 3 yr (data not presented), temperature by itself probably does not explain between-year variation in thifensulfuron plus sethoxydim damage to soybean. In contrast, significant rain fell shortly after treatment in 1993, whereas it was drier for up to 2 wk after treatment in 1992 and 1994 (Figure 1). Periods of extended dryness after treatment probably prevented treated soybeans from fully expressing their normal high potential for yield component compensation in 1992 and 1994, compared to moister conditions in 1993 (Figure 3). Long-term moisture stress probably hampered plant recovery following initial herbicide damage. Rainfall was above normal from June to October in 1993, but it was below normal in June in 1992 and 1994 and in July in 1994. Mean soybean yields of untreated weeded check plots were 82, 100, and 87% of the yield goals for which soybeans were fertilized in 1992, 1993, and 1994, respectively.

Suggestions for Improving Methodology

Steps need be taken to achieve greater regression model and measurement predictability and reproducibility if either stunting or ground cover are to be used to estimate relative crop yield loss. Although ground cover "explained" greater amounts of model equation variability than did either relative herbicide rate or stunting, R^2 values were still low, and models differed among years despite equation normalization (Figure 2). Linear regression equations relating relative corn yield to crop ground cover after sethoxydim treatment of susceptible corn varieties had much greater R^2 values and were more consistent over 3 yr (data not shown). Sethoxydim damaged corn and reduced relative yield more than sethoxydim plus thifensulfuron damaged soybean. The reproducibility of such relationships among years probably depends on the specific herbicide and crop combination under study. Perhaps such relationships are more consistent when herbicides reduce crop stand, when herbicide damage is very severe, and when the crop has limited potential for yield component compensation (i.e., soybeans have greater yield component compensation ability than corn). Herbicide translocation patterns and mode of action are probably important as well. Herbicides that translocate to shoot apical and lateral bud meristems and kill them will prevent later leaf outgrowth, canopy development, and yield component formation. In contrast, poorly translocated, contact herbicides only damage expanded sprayed foliage but allow sub-

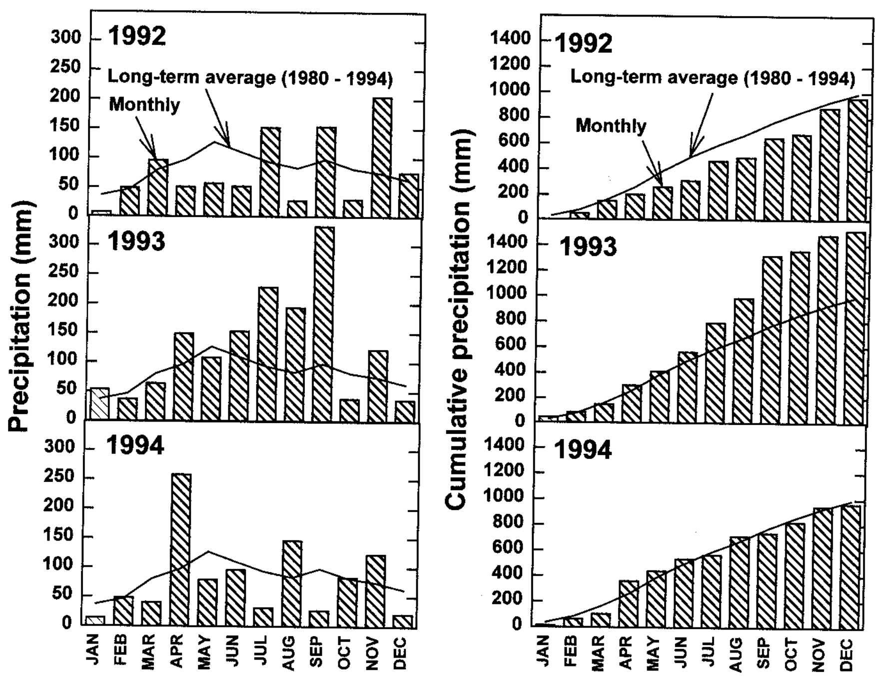

FIGURE 3. Monthly precipitation (bars) and cumulative monthly precipitation (bars) in 1992 to 1994 with the respective long-term averages (1980 to 1994) (lines) at the Bradford Experimental Farm near Columbia, MO.

sequent canopy development and yield component formation from shoot apical and lateral bud meristems. These suggestions can only be tested by examining additional herbicide and crop combinations.

Year-to-year and site-to-site variation in date of planting, date of herbicide treatment in relation to crop growth stage, date of photograph collection after treatment, and weather conditions will likely affect reproducibility by influencing canopy development rate. In this research, ground cover ranged between approximately 5 and 60% in 1992, between 20 and 65% in 1993, and between 5 and 50% in 1994 over all treatments (Figure 2). The untreated soybean canopy was greater when measured in 1992 and 1993 than in 1994. Cover or stunting observations could be made when untreated soybeans reach a predetermined standard percent ground cover or height, respectively. Also, growing degree-day models could help predict crop phenology from yearly weather data, instead of relying on calendar dates.

Steps also need to be taken to reduce the time and cost of data collection and processing. Automating photograph collection and record keeping in the field and using rapidly developing digital cameras instead of still video cameras would eliminate the time and labor spent in digitizing photographs for later computer image analysis. Use of infrared photography would allow more automated use of image analysis software for cover estimation. Rapid advances in image analysis software may eventually allow use of computer algorithms for automatically measuring ground cover and summarizing results, expediting use of this technology.

Sources of Materials

[1] Names are necessary to report factually on available data; however, the USDA neither guarantees nor warrants the standard of the product, and the use of the name by the USDA implies no approval of the product to the exclusion of others that may also be suitable.

[2] Teejet flat fan spray nozzle SS 8001 LP, Spraying Systems Co., Wheaton, IL 60187.

[3] Xapshot or RC 570 still video camera, Cannon U.S.A. Inc., Still Video Systems Division, 1 Canon Plaza, Lake Success, NY 11024.

[4] SV-PC SV-Digitizer Still Video Board, Cannon U.S.A. Inc., Still Video Systems Division, 3 Dakota Dr., Lake Success, NY 11024.

[5] SigmaScan version 1.0 and Mocha software, Jandel Scientific, 2591 Kerner Boulevard, San Rafael, CA 94901.

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