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TOLERANCE OF CEREALS TO POST- EMERGENCE WEED HARROWING

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Summary

This study defines crop tolerance to post-emergence weed harrowing as the combined effect of crop resistance and crop recovery. Crop resistance is the ability of the crop to resist soil covering and recovery is the ability to recover in terms of yield. In two experiments, resistance, recovery and tolerance were quantified in barley, oat, wheat and triticale by a new method based on digital image analysis. Important differences in resistance, recovery and tolerance among species were seen and resistance was not linked to recovery. Oat showed higher resistance than wheat, and barley. Triticale showed the lowest resistance. Oat and barley showed both lower ability to recover from soil covering than wheat, and triticale showed complete recovery. Triticale was the most tolerant species followed by wheat, oat and barley. Differences in tolerance caused species dependent crop yield losses in weed-free environments in the range of 0 to 10% for a practical relevant aggressiveness of weed harrowing.

Résumé

La tolérance des céréales au sarclage dépend à la fois de l'adaptabilité de ces céréales au sarclage et de leur résilience suite à d'éventuels dommages. Lors de deux essais, nous avons comparé la résistance et la tolérance de l'orge, de l'avoine, du triticale et du blé au sarclage en utilisant une nouvelle méthode basée sur l'analyse d'images digitales. L'avoine a démontré une plus grande résistance au sarclage que le blé et l'orge. Le triticale était la céréale la moins résistante au sarclage. Les céréales se font recouvrir par de la terre lors des opérations de désherbage. L'orge et l'avoine ont démontré une moins grande capacité de résilience après s'être fait recouvrir par la terre que l'avoine, le triticale et le blé qui récupèrent complètement. Les différences de tolérance entre les espèces se sont reflété dans les rendements des céréales. Les céréales furent cultivées dans un environnement sans aucune mauvaises herbes. Le sarclage aura causé des dommages résultant en des diminutions de rendements de 0 à 10% pour les intensités de sarclage qui ont une relevance pratique.

Introduction

Crop damages associated with weed harrowing cannot be neglected, because damage may result in lack of positive crop yield response or even negative response when weeds are controlled by weed harrowing (RASMUSSEN, 1991; KIRKLAND, 1995, RASMUSSEN & SVENNINGSEN, 1995). For example, RASMUSSEN & SVENNINGSEN (1995) found that 85% weed control reduced crop yield by 8 % in spring barley.

The importance of crop damage is stressed by the fact that an inverse relation between weed control and crop damage exists, which limits the possibilities to combine high degrees of weed control and undamaged crop plants (RASMUSSEN, 1991). Therefore, selectivity, which expresses the relation between weed control and crop damage, has been emphasised within weed harrowing research (RASMUSSEN, 1992; KURSTJENS & PERDOK, 2000; JENSEN *et al*., 2004).

An important aspect of selectivity is crop response to damage in terms of yield. A limited number of studies have focused on yield response in weed-free environments but there is evidence that different species and cultivars respond differently to weed harrowing. Lupin (*Lupinus luteus* L. and *Lupinus angustifolius* L.) recovered better from soil covering than field pea (*Pisum sativum* L.) (JENSEN *et al,* 2004) and tall spring barley cultivars with high leaf area index (LAI) were damage more than shorter cultivars with lower LAI (RASMUSSEN *et a*l., 2004).

To increase our understanding of the negative impacts on crop yield, crop tolerance may be an essential concept. Until now, however, the concept has been used inconsistently. KURSTJENS & KROPFF (2001) did not use the concept explicit, but they emphasized the importance to separate: (1) the damaging process during harrowing and (2) the subsequent recovery process. JENSEN *et al*. (2004) also divided crop response into two time related categories; (1) the initial damage effect, which reflects the ability of the crop to resist soil covering, and (2) the recovery effect, which reflects the ability of the crop to overcome soil covering. They linked tolerance to the recovery process and thereby excluded the initial damage effect from tolerance. This contradicts the way RASMUSSEN *et al*. (2004) conceptualized the concept. In their terminology, tolerance includes both aspects; (1) the initial damage effect, and (2) the subsequent recovery effect.

In order to tighten up the terminology, we suggest that crop tolerance should cover the combined capacity of the crop to resist damages and to recover from them. Hereby, resistance and recovery becomes key components in the tolerance concept.

One main challenge in determining crop tolerance is to assess the initial damage in an objective way. Crop density reduction constitutes a reliable measure in some crops but in cereals and grain legumes, crop soil cover is the primary mode of damage (JENSEN *et al*., 2004).

Crop soil cover has until now been visually assessed. Nevertheless it has often been pointed out, that more objective methods are needed. JENSEN *et al*. (2004) discussed the weaknesses linked to visual assessment but they applied this assessment method “for lack of a better one”.

Parallel to this study, we have developed an objective and reproducible method based on digital image analysis to determine crop soil cover (NØRREMARK, 2005). This method ensures objective measurements and reduces risks of biased assessments. In this study, we used the new method to investigate to what extend there exists differences in tolerance among different species of cereals.

Materials and methods

Field experiments

Two identical spring tine harrowing experiments were carried out in Taastrup at the Royal Veterinary and Agricultural University of Denmark, 20 km west of Copenhagen to investigate resistance, recovery and tolerance in spring barley (*Hordeum vulgare spp. Landon*), spring wheat (*Triticum aestivum spp Ameretto*), spring oat (*Avena sativa spp Revisor*) and spring triticale (*Triticosecale spp. Legalo*) without interference from weeds.

Row width was 12 cm, and seed rate was adjusted for seed weight to give a target established population of 300-350 plants m^{-2}. Actual counts of crop density, however, showed barley: 271 plants, oat: 357 plants, wheat: 346 plants and triticale 219 plants m^{-2}.

One experiment was conducted in an organic growing system and the other in a conventional growing system. Both experiments were on sandy loam. In the conventional growing systems weeds were successfully controlled by herbicides to exclude competition from weeds. In the organic growing system, weed biomass was limited in untreated plots (6.8 g m^{-2} in beginning of July) so that competition was presumed to be insignificant.

Both experiments were arranged as a split-plot design with four replicate blocks. Crop species were applied to main plots, with four intensities of harrowing (0, 1, 2 and 3 passes) applied as a sub-plot treatment giving 64 plots in each experiment. Each sub-plot was 3 m x 10 m in the conventional system and 3 m x 11.5 m in the organic growing system. Grain yield was harvested in 1.5 m x 10 m area (1.5 m x 11.5 m area in the organic growing system).

The field experiments included progressive series of harrowing intensities to establish varying degrees of soil covering in the range of approximately 0-70% crop soil cover. Each of the species was harrowed with the same intensities. The range of harrowing intensities was established by an increasing number of passes (0, 1, 2 and 3) with an Einböck spring-tine weeder in growth stage 12-13 (BBCH). Tool adjustment and driving speed were kept constant, which means that different relations between crop soil cover and number of passes originated from difference in resistance.

The different crop species were harvested at maturity, grain yield was weighted, dried and yield was adjusted to a water content of 15%.

Assessments

The day after harrowing four images per plot were acquired with a Kodak DX 4530 digital camera with automatic white balancing, shutter speed and aperture value. The image plane was parallel to soil surface and each image covered 1.2 m x 1 m. The image size was 2580 pixels x 1932 pixels. The camera was mounted on a tripod to ensure uniform distance between soil surface and camera. The images were acquired between 10 am to 2.30 pm. The sky was cloudy during the whole photo session.

All images were analyzed according to the procedure given in NØRREMARK (2005). The MATLAB software package (MathWorks, MA, USA) was used to determine the Excessive Green Index (MEYER *et al*., 1998) and to segment the images into two categories, plants and background independent of light conditions. Hereby, the percentage of green pixels was calculated. Percentage of green pixels is referred to as percentage *green cover*.

Statistics

Green cover and crop yield was initially subjected to analysis of variance (ANOVA). Growing system was included as a factor and block effects were nested within growing system. As a consequence of the split-plot design, main-plot effects were tested against mean squares (MS) of the interaction between main plot and block. In order to stabilize variance, green cover was log-transformed, while crop yield data was not transformed.

Resistance curves, which express the relation between green cover and number of passes, were tested by using the exponential decay function

$$Y_i = a_i \exp(-b_i P) \qquad \text{Equation (1)}$$

where Y_i is the green cover, a_i and b_i are regression parameters for each crop species, i, and P is the number of passes. Parameter a_i denotes green cover in untreated plots and b_i denotes the relative green cover decrease of each pass with the harrow.

Successive F-tests were used to determine whether different exponential curves were needed for crop species according to the sum of squares reduction test (BROWN & ROTHERY, 1993). An F-test provided a test of whether a more complex model provided a better overall description of the observed data. Model comparisons were carried out in turn to omit non-significant factor effects on parameters.

Curve fitting was performed by the NLIN procedure in SAS (SAS Institute Inc., CA, USA) and log-transformation was used for green cover. Parameters and standard errors of parameters were not affected by the transformation because the transform-both-sides technique was used (CARROLL & RUPPERT, 1988).

Resistance curves, which express the relation between crop soil cover (CC) and number of passes, was deduced from Equation (1)

$$CC = 100(1-\exp(-b_i P)) \qquad \text{Equation (2)}$$

Recovery curves, which express the relation between crop yield and green cover, were tested by linear regression.

$$Y = a_i + b_i X \qquad \text{Equation (3)}$$

where Y_i is the crop yield, a_i and b_i are regression parameters for each crop species, i, and X is green cover.

Recovery curves expressing the relation between percentage crop yield reduction (Y_{red}) and crop soil cover were calculated on the basis of Equation (3). Percentage crop yield reduction was calculated relative to crop yield in untreated plots and crop soil cover was calculated as percentage reduction in green cover.

Tolerance curves, which express the tolerance of cereals as crop yield response to increasing number of passes, were fitted by linear regression.

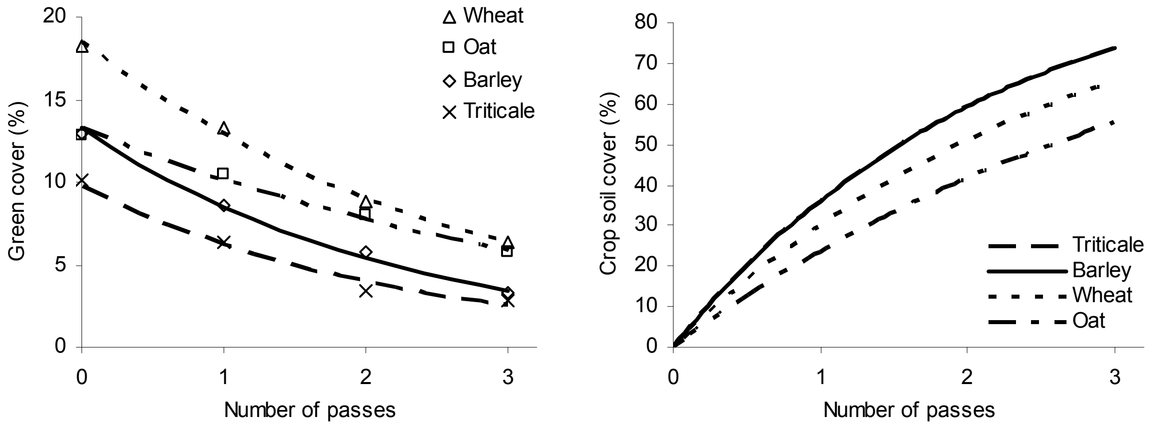
To test whether the exponential decay model and the linear regression model described resistance and recovery curves well, the models were tested against a full ANOVA model to test the lack-of-fit. Comparison between models was done on the basis of F-tests.

If statistical test showed no significant (*P* < 0.05) difference between parameters for different crop species, only one parameter is presented.

Results

In the following presentation, the two experiments have been merged because ANOVA showed no three-way interactions between species, intensity of harrowing and growing system in terms of green cover and crop yield (*P* > 0.05). In statistical terms, this study focuses on the species harrowing interactions because significant interactions imply that different species respond differently to weed harrowing. The non-significant three-way interactions show that the species harrowing interactions of interest were unaffected by growing system.

Regression analysis of the green cover showed that triticale and barley were less resistant to weed harrowing than wheat and oat (Figure 1A). According to the *b* values given in Table I, the resistance of triticale and barley was alike whereas oat was more resistant than wheat.



A **B**

Figure 1. Resistance of spring cereals expressed as green cover response (A) or crop soil cover response (B) to increasing number of passes. Curves in the left panel are fitted according to Equation 1 (parameters given in Table I). Curves in the right panel are estimated on the basis of Equation 2 and parameters from Table I.

Figure 1. La résistance des céréales de printemps au sarclage exprimée en terme (A) de la couverture verte des plantes ou (B) de la couverture du sol par les plantes en relation du nombre de passages. Les courbes dans la partie gauche du graphique furent harmonisées à l'équation 1 dont les paramètres se trouvent dans la table 1. Les courbes dans la partie droite du graphique furent harmonisées à l'équation 2 dont les paramètres se trouvent également dans le tableau 1.

In order to express the crop response as crop soil cover, which matches previous presentations in papers based on visual assessment, the percentage reduction of green cover by increasing passes was estimated (Figure 1B). The impact of three passes in triticale and barley was 74 % crop soil cover, in wheat 66 % and in oat 55%.

Parameter *a*, which expresses the green cover in the untreated plots, showed that wheat covered 18.4% of the ground in untreated plots, oat and barley covered 13,3 % and triticale covered only 9.8% (Table I). Hence, there was no proportionality between green cover in

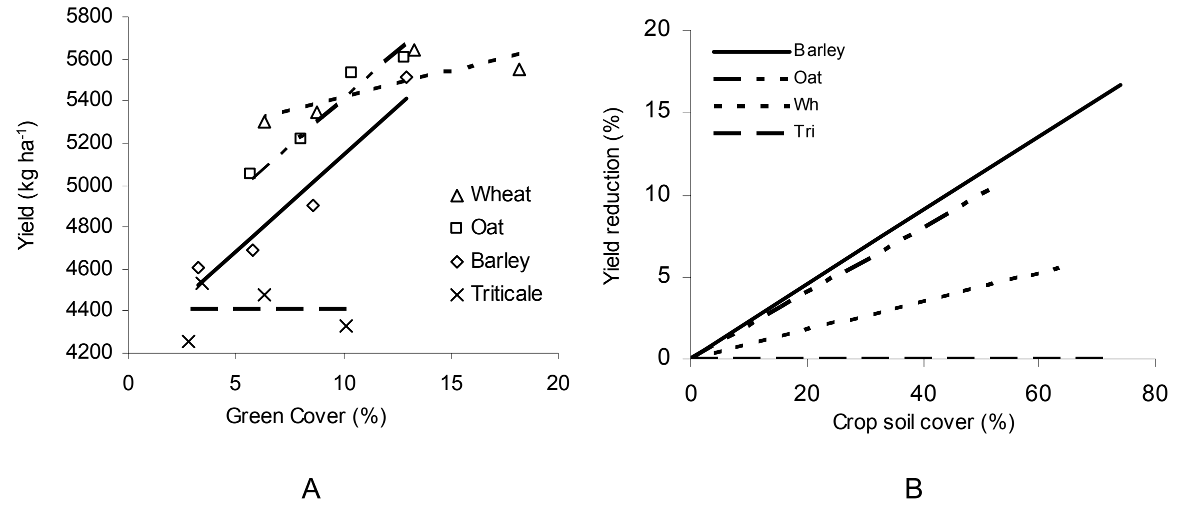
Table I. Estimates of parameters that reflect resistance to weed harrowing on the basis of Equation (1). Parameter *a* denotes the percentage of green cover in untreated plots and parameter *b* denotes the relative green cover decrease of each pass with the harrow. Standard deviation in brackets.

Tableau I. Estimations des paramètres qui reflètent la résistance au sarclage sur la base de l'équation (1). Le paramètre *a* représente le pourcentage de couverture verte des plantes dans les parcelles de contrôle sans passage et le paramètre b représente la diminution relative de cette couverture végétales suite à chaque passage. La déviation standard est indiquée entre parenthèse.

	Paramter a	*Parameter b*
Wheat	18.4 (1.03)	0.36 (0.030)
Oat	13.3 (0.47)	0.27 (0.024)
Barley	13.3 (0.47)	0.45 (0.019)
Triticale	9.8 (0.42)	0.45 (0.019)

untreated plots (Parameter *a*) and resistance (Parameter *b*). For example, barley and oat had equal values of green cover in untreated plots but nevertheless; barley was less resistance to harrowing than oat (Table I).

The different species showed different recovery abilities. For every percent loss of green cover, barley and oat had a yield loss of 91kg ha^{-1} (Figure 2A). Wheat yield was reduced with 25 kg ha^{-1} and triticale did not react to crop covering (Figure 2A). Hence, triticale recovered extremely well whereas barley and oat were highly susceptible to crop soil cover. The relative yield loss expressed as a function of crop soil cover (Figure 2B) showed that 20% crop soil cover, which is recommended as acceptable crop damage in Denmark, resulted in 4.5 % crop yield loss in barley, 3.9% in oat, and 1.7 % in wheat.



A B

Figure 2. Recovery of spring cereals expressed as crop yield response to green cover (A) or crop yield reduction to crop soil cover (B). Curves in the left panel are fitted according to Equation 3, b. The b-parameters: wheat 25.18, oat and barley 91.32, triticale 0. Curves in the right panel are estimated on the basis of Equation 3. *b*-parameters are the same as in (A).

Figure 2. La résilience des céréales de printemps suite au sarclage exprimée comme (A) le rendement en fonction de la couverture végétale ou (B) comme la réduction du rendement par rapport à la surface de sol visible. Les courbes dans la partie gauche du graphique furent harmonisées à l'équation 3. Les paramètres b: le blé 25.18, l'avoine et l'orge 91.32, le triticale 0. Les courbes de la partie droite du tableau sont estimées à partir de l'équation 3. Les parameters sont les mêmes que pour (A).

Species are ranked differently according to resistance and recovery, which implies that tolerance cannot be deduced from either resistance or recovery.

Figure 3 shows how the species tolerated increasing passes of harrowing. Barley being the crop with the lowest resistance as well as the lowest recovery had low tolerance to harrowing. This resulted in a crop yield loss at 293 kg at every pass of the harrow according to regression analysis. Oat being the crop with the highest resistance but a low recovery lost 199 kg with every pass, and wheat with medium resistance but high recovery lost only 105 kg. Triticale was indeed very tolerant due to its high ability to recover. No yield loss was observed for triticale.

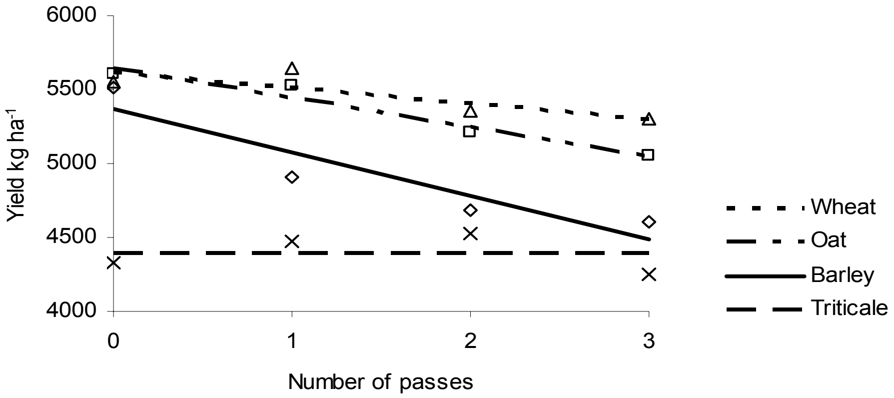


Figure 3. Tolerance of spring cereals expressed as crop yield response to increasing number of passes.

Figure 3. La tolérance des céréales d'été exprimée comme la relation entre leurs rendements et un nombre croissant de passages.

Discussion

This experiment focuses on crop tolerance as the combined capacity of the crop to resist and recover from damages. Previously, a number of studies have investigated tolerance (LAFOND & KATTEL, 1992; RASMUSSEN *et al.*, (2004). Tolerance, however, expressed as crop yield response to a given mechanical treatment is associated with some major weaknesses. Information about tolerance does not contain information about the real-time impact on the crop and cannot be used to make real-time adjustments of the harrow. Therefore, a number of studies have focused on the real-time impact on the crop (Rasmussen, 1992; Rydberg, 1994) and a few studies have investigated the relationship between crop soil cover (the real-time impact) and crop yield (RASMUSSEN, 1991; JENSEN *et al.*, 2004). The biased nature of crop soil cover, which is based on visual assessments of the crop, means that this relation (recovery) has been difficult to quantify properly (JENSEN *et al.*, 2004). Crop resistance to mechanical weeding, has also been difficult to quantify, because there is no standard for a given mechanical treatment like "one pass with the harrow". This is due to the fact that no clear relation between type and adjustment of the harrow, soil characteristics and the impacts on the crop exists.

Objective and reproducible assessment of the real-time impact on the crop by means of image analysis opens new possibilities to quantify resistance and recovery. In this study we have used green cover in statistical analysis in opposite to previous studies, which used crop soil cover. Green cover can easily be converted to crop soil cover, but green cover is a more appropriate response than crop soil cover, because it is an absolute measure. Crop soil cover, which previously has been expressed relative to untreated plots, implies that all untreated plots by definition are 0. This limits the power of statistical analysis.

In this experiment, the crops showed different ability to resist soil covering. For example, the effect of one pass could be quantified to 24 % crop soil cover in oat and 36 % crop soil cover in barley (Figure 1). The ability to resist soil covering was not related to green cover in untreated plots and it has not been possible to reveal the reason for the differences in resistance. One factor that might influence the resistance is plant density. Oat had 357 plants m^{-2} and barley, with the lower resistance had only 272 plants m^{-2}. Nevertheless, Triticale had a plant density even lover than barley, 207 plants m^{-2}, but resistance was identical with barley. Therefore, plant density seems not to be a major factor controlling resistance.

This study was conducted with only one variety for each species but it is quite conceivable that different varieties hold different resistance and that resistance can be connected to morphological traits like competitiveness (DIDON, 2002) and tolerance (RASMUSSEN *et al*., 2004). Future studies, however, have to reveal how morphological traits are related to resistance.

To obtain full benefit of knowledge about resistance in real-time adjustment of the harrow, it is necessary to have knowledge abut recovery. This study shows that different species hold different ability to recover. Barley and triticale, being the crops with the lowest resistance, represented the lowest and highest ability to recover, and oat showing the best resistance did not recover very well. It is quite remarkable, that the crops showed significant variation in capacity to resist, recover and tolerate weed harrowing. In accordance with RASMUSSEN *et al*. (2004) who tested spring barley cultivars, we found that a realistic difference between crops with high and low tolerance corresponds to the range of 0% to 10% crop yield loss for treatments which are considered relevant in a practical context.

Conclusion

This study shows that there exists important differences in resistance, recovery and tolerance among cereal species and that resistance is not necessarily linked to recovery. This implies, that future research, which aims to integrate crop tolerance into decision support systems about the optimal treatment should consider crop resistance as well as crop recovery.

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