Assessment of leaf cover and crop soil cover in weed harrowing research using digital images

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SHORT TITLE: Assessment of crop soil cover

SUMMARY

Objective assessment of crop soil cover, defined as the percentage of leaf cover that has been buried in soil due to weed harrowing, is crucial to further progress in post-emergence weed harrowing research. Up to now, crop soil cover has been assessed by visual scores, which are biased and context dependent. The aim of this study was to investigate whether digital image analysis is a feasible method to estimate crop soil cover in the early growth stages of cereals. Two main questions were examined: (1) how to capture suitable digital images under field conditions with a standard high-resolution digital camera and (2) how to analyse the images with an automated digital image analysis procedure. The importance of light conditions, camera angle, size of recorded area, growth stage and direction of harrowing were investigated in order to establish a standard for image capture and an automated image analysis procedure based on the excess green colour index was developed. The study shows that the automated digital image analysis procedure provided reliable estimations of leaf cover, defined as the as the proportion of pixels in digital images determined to be green, which were used to estimate crop soil cover. A standard for image capture is suggested and it is recommended to use digital image analysis to estimated crop soil cover in future research. The prospects of using digital image analysis in future weed harrowing research are discussed.

Keywords: Physical weed control, crop damage, crop tolerance, crop resistance, crop recovery, digital image analysis, the excess green colour index

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Introduction

In a recent paper on guidelines for physical weed control research, Vanhala *et al*. (2004) emphasise the need of unbiased methods to assess the immediate crop damages associated with harrowing.

The importance of crop damage associated with weed harrowing has often been demonstrated (Jensen *et al*., 2004) and Rasmussen (1991; 1993a) showed that crop soil cover is a valuable input in predictive models that aim to determine the optimal intensity of harrowing.

The immediate crop response to harrowing is most often expressed in terms of crop soil cover, which is the percentage of the above ground crop parts that have been buried in soil (Rasmussen, 1991). This measure is assessed by visual scores, which are context dependent and biased. Even trained people assess crop soil cover rather individually. One assessor may estimate a specified treatment at 20% crop soil cover while another may estimate it at 40% (Rasmussen *et al*., 1997).

Nevertheless, crop soil cover has been and still is used for the lack of any better (Jensen *et al*., 2004). The biased nature of visual scores is not vital in experiments where the main objective is to compare different treatments with the same experiment. However, when results from different experiments are of interest, it is indeed very problematic to use visual ratings. For example, Jensen *et al*. (2004) quantified the ability of lupin (*Lupinus albus* L. and *L. luteus* L.) to resist and tolerate crop soil cover from post-emergence weed harrowing without being able to make reliable comparisons to previous studies in pea (*Pisum sativum* L.). They doubted that their assessments of crop soil cover in lupin were comparable to those in earlier studies in pea conducted by Rasmussen (1993b). In consequence, visual assessment of crop soil cover hampers communication and learning within the scientific community.

Crop soil cover is mainly used in Europe (Kurstjens & Kropff, 2001, Jensen *et al*., 2004, Melander *et al*., 2005) whereas most research papers from USA and Canada express crop damage as crop density reductions (Mohler & Frisch, 1997; Leblanc & Cloutier, 2000). Jensen *et al*. (2004) discussed advantages and disadvantages of both measures and concluded that crop soil cover is the only practicable real-time method in cereals and grain legumes, because it is impossible to distinguish and count single crop plants immediately after harrowing. Plants are more or less buried in soil, which make them inseparable.

Previously, two objective assessment methods of crop soil cover have been tried out: (1) wooden sticks placed in crop rows to measure the height of the ridges created by the mechanical implements (Melander, 1997; Cirujeda *et al*., 2003; Melander *et al*., 2003) and (2) photoelectric sensor techniques where light reflectance from the crop canopy is measured by sensors (Rasmussen, 1996; Rasmussen *et al*., 1997; Engelke, 2001; Hansen, 2005).

Wooden sticks are not useful for post-emergence weed harrowing because harrowing has no ridging effect but the method has some potential in row-cultivation where soil is thrown into the rows. There has been an increase in work on remote sensing by photoelectric sensors within site-specific weed management (Gerhards & Christensen, 2003; Scotford & Miller, 2005) but results in the context of weed harrowing are either negative or inconclusive when trying to establish a standard method (Rasmussen, 1996; Rasmussen *et al*., 1997; Engelke, 2001, Hansen, 2005).

Rasmussen (1996) and Rasmussen *et al*. (1997) showed positive correlations between crop soil cover assessed visually and by photoelectric sensors but the relation between assessments was context dependent. Rasmussen *et al*. (1997) concluded that variability in ground colour rendered sensor assessments inaccurate. Engelke (2001) found that the precision of photoelectric sensors used in the early growth stages of cereals was too low to be useful in automated adjustments of weed harrowing. Hansen (2005) used photoelectric sensors to investigate whether different barley genotypes responded differently to weed harrowing but without indicating the reliability of his assessments.

In a recent review on canopy spectral remote sensing, Thorp and Tian (2004) concluded that the presence of variable soil backgrounds still complicates the spectral response and hinders the analysis of vegetative cover. Unfortunately, the review was mostly concerned with the canopy reflectance in the near infrared (NIR) and red wavebands. The study by Marchant *et al*. (2001) who utilized three wavebands, red, near-infra-red (NIR) and green, was not included in the review. They obtained satisfactory segmentation of vegetation from background with a combination of these three wavebands plus introduction of a novel classification method (alpha-method). Unfortunately, this method requires a dedicated sensor and it has not been tested in crops that have been disturbed by mechanical weed control.

In order to develop a standard for objective and reproducible assessment of crop soil cover, we chose digital image analysis instead of photoelectric sensors because digital cameras are widespread and because image processing is used widely in research on leaf cover assessment (Thorp and Tian, 2004).

Our objectives were (1) to investigate whether digital image analysis provides reliable estimations of crop soil cover in the early crop growth stages of cereals and (2) to suggest a standard for the image capture procedure.

Materials and methods

Terminology and experimental approach

In this study, leaf cover is defined as the proportion of pixels in digital images determined to be green, and crop soil cover, defined as the percentage of leaf cover that has been buried in soil due to weed harrowing, is calculated as the leaf cover differences between control plots and harrowed plots divided by the leaf cover in control plots within each block replication. Leaf cover and crop soil cover are both expressed in percentage by multiplying by 100.

This study focus on factors that could be assumed to influence the estimation of leaf cover and thereby crop soil cover from digital images such as camera tilt angle, light conditions, size of recorded areas, direction of harrowing and growth stage of the crop. It is based on an innovative approach, which started with two main questions, (1) how to acquire useful digital images with a standard high-resolution digital camera (the image capture challenge) and (2) how to develop an appropriate algorithm and automated analysis procedure within a standard software package (the image analysis challenge) to calculate the proportion of green pixels in digital images. There was no attempt to discriminate crop and weeds because it was considered unimportant in the perspective of early post-emergence weed harrowing. In most cases weeds are assumed to make up only a few percent of the total leaf cover.

The challenges associated with the image capture and the digital image analysis were mutually connected. The image-processing procedure was changed several times during the study to cope with the different characteristics of the images acquired and the work with the image analysis also influenced the image-capture scheme.

The innovative working process with the image analysis challenge is described and illustrated in the materials and methods section, whereas the outcome of the work with the image capture challenge is described the result section.

Field experiments

Digital images originated from two field experiments (experiment 1 and 2) with weed harrowing in organic winter wheat (cv Complet) mixed with approximately 10% winter rye (cv Caroass). The mixture was arranged in order to guarantee that the harvested crop, could be distinguished from other non-organic winter wheat.

Both experiments were conducted on a sandy loam at Bakkegården, which is an experimental farm owned by The Royal Veterinary and Agricultural University, Denmark. The farm is organic, which means that pesticides were not used.

Experiment 1 was originally planned to investigate the importance of timing of weed harrowing in order to achieve efficient weed control and positive crop yield response, and the results have been reported elsewhere (Rasmussen & Nørremark, 2006).

Weed harrowing was carried out at three growth stages (BBCH), 12, 22 and 23 and in a combination of all growth stages (12+22+23), hereafter called the combined growth stage. Harrowing was on 9 December 2003, 14 April 2004 and 30 April 2004. At each growth stage, the crop was harrowed in the same direction 1, 2, or 3 times on the same day to create a progressive series of intensities. The planned targets of the graded levels of harrowing in each of the three specific growth stages were 0 (control), 30, 60 and 90% crop soil cover in order to cover the whole range of intensities from normal to very aggressive. The practical adjustment of the aggressiveness of harrowing was adjusted on the basis of visual assessments of the whole plots. Driving speed and tine angle was adjusted so one pass gave approximately 30% crop soil cover. After the settings of driving speed and tine angles had been chosen, all plots were harrowed with the same adjustment.

Harrowing was done with a 3 m wide weed harrow manufactured by Einböck (Einböck GmbH & CoKG, A-4751 Dorf an der Pram, Austria). At growth stage 12, the angle of tines was adjusted to the highest negative value possible (Vanhala *et al*., 2004) giving a very gentle treatment. Driving speed was 3 km h^{-1}. At growth stage 22 and 23, the angle of tines was adjusted to the highest positive value possible (Vanhala *et al*., 2004) giving the most aggressive treatment. Driving speed was 8 km h^{-1}. Higher driving speed did not increase the intensity in terms of crop soil cover.

The planned targets were practicable in autumn 2003 but not in spring 2004 where the soil was too compacted to achieve high degrees of crop soil cover. Based on visual assessments, about 20% crop soil cover was achievable after 3 successive passes at growth stage 22 (14 April 2004) and at growth stage 23 (30 April 2004) only about 20% crop soil cover was achievable.

Growth stage was assigned to main plots, with the four intensities of harrowing applied as a sub-plot treatment. Growth stage was on main plots because this saved time when plots were harrowed. Each sub-plot was 14 m long and 3 m wide.

All digital images were taken in 2004, which means that there were no recordings from the earliest growth stages in autumn 2003. To investigate the utility and possible limitations of the digital image analysis procedure in very early growth stages, a second experiment (experiment 2) was carried out in autumn 2004 to question whether it is possible to discriminate treatments when leaf cover approaches 1-3% of the ground surface.

In experiment 2, three progressive series of harrowing with 4 graded levels of harrowing was carried out in growth stage (BBCH) 11 when the first developed leaf was about 4-5 cm long. One series was harrowed along the crop rows, one across the crop rows and one in both directions, which means that harrowing was done in plots that were drilled in two perpendicular directions (double seed rate). The double seed rate was used because it was doubted whether it would be possible to discriminate treatments at the normal seed rate due to very low levels of leaf cover. The experiment was designed as three randomised block experiments within each direction; along, across and both. The angle of the tine on the Einböck harrow was adjusted to give the gentlest treatment possible, and driving speed was adjusted to give the graded levels of treatment (0 km h^{-1}, 2 km h^{-1}, 3.5 km h^{-1} and 5 km h^{-1}). The driving speed was adjusted instead of the number of passes as in experiment 1 because an increasing number of passes created too aggressive treatments.

Image capture

In all photo sessions, four images were taken in each plot, and a total of 2112 images were recorded and analysed. Of these, 512 images were used to interpret the weed control experiment (Experiment 1) as presented in Rasmussen & Nørremark (2006).

The images, 2288 pixels horizontally by 1712 pixels vertically with 24-bit depth, were taken using a red, green, blue (RGB) digital camera, Olympus C750UZ (Olympus Optical Co., Ltd.). An 11 mm focal length lens was used with a fixed F-stop of 3.2. The digital image analysis procedure makes no special demands on the camera in terms of filters, white balancing, shutter speed or aperture value. The only requirement is that the images are focused and correctly exposed. To avoid random variation in the camera angle, a tripod was used to fix the position of the camera.

To investigate the importance of light source, a series of images were captured in bright and diffuse sunlight on 14 April and 30 April in experiment 1 (Table 1). To create diffuse sunlight, the sun was screened with a bright cloth, which made shadows from the crop plants imperceptible. Images captured on 14 April were taken with camera tilt angle 30^0 and on 30 April with camera angle 45^0 according to Fig. 1.

Fig. 1 Illustration of camera angles relative to the ground plane and the direction of harrowing