Guidelines for physical weed control research: flame weeding, weed harrowing and intra-row cultivation

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Abstract

A prerequisite for good research is the use of appropriate methodology. In order to aggregate sound research methodology, this paper presents some tentative guidelines for physical weed control research in general, and flame weeding, weed harrowing and intra-row cultivation in particular. Issues include the adjustment and use of mechanical weeders and other equipment, the recording of impact factors that affect weeding performance, methods to assess effectiveness, the layout of treatment plots, and the conceptual models underlying the experimental designs (e.g. factorial comparison, dose response).

First of all, the research aims need to be clearly defined, an appropriate experimental design produced and statistical methods chosen accordingly. Suggestions on how to do this are given. For assessments, quantitative measures would be ideal, but as they require more resources, visual classification may in some cases be more feasible. The timing of assessment affects the results and their interpretation.

When describing the weeds and crops, one should list the crops and the most abundantly present weed species involved, giving their density and growth stages at the time of treatment. The location of the experimental field, soil type, soil moisture and amount of fertilization should be given, as well as weather conditions at the time of treatment.

The researcher should describe the weed control equipment and adjustments accurately, preferably according to the prevailing practice within the discipline. Things to record are e.g. gas pressure, burner properties, burner cover dimensions and LPG consumption in flame weeding; speed, angle of tines, number of passes and direction in weed harrowing.

The authors hope this paper will increase comparability among experiments, help less experienced scientists to prevent mistakes and essential omissions, and foster the advance of knowledge on non-chemical weed management.

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1 Introduction

Experimentation is indispensable to knowledge development and transfer in all stages and at all levels. From trying out new ideas or weeder prototypes, systematic comparison of machines, sets of practical management guidelines and complete weed management systems, to their demonstration to farmers and joint learning processes, experiments are the proof of the pudding in deciding which machine to buy, testing hypotheses, gathering fundamental insights in the working mechanisms, and assessing parameters for models. Whatever the approach and objective, tailoring labour- and cost-efficient experiments that allow sound and sufficiently precise inferences on the predefined issues is an art that develops over the years. New experimental methods are often at the basis of scientific and technological breakthroughs. Therefore, exchanging experiences on existing methodology, identifying problems and flaws, and searching ways to overcome them within the constraints of time and money is an important role of communities like the EWRS working group on Physical and Cultural Weed Control.

Since the working group was established in 1994, several contributions and roundtable discussions have dealt with methodology. International exchange of research staff has assisted in the dissemination of advancements and new approaches as well. In the meantime, the research area of non-chemical weed management has matured and nowadays includes a wide variety of approaches, with increasing crosslinks to other areas in weed science. As many methodological topics specific to non-chemical weed control are not yet adequately addressed in textbooks on statistics and experimental design (Gomez & Gomez, 1984; Little and Hills, 1978) or experimental methodology in weed science (Burril *et al.*, 1976; Frans *et al.*, 1986), the authors feel a need to document insights gathered in the last 15 years. Issues include the adjustment and use of mechanical weeders and other equipment, the recording of impact factors that affect weeding performance, methods to assess effectiveness, the layout of treatment plots, and the conceptual models underlying the experimental designs (e.g. factorial comparison, dose response).

This work should be perceived as a working paper to collect scattered knowledge and stimulate discussions. It is open for improvement. Where possible, we aim to define guidelines. In other occasions, present methodological flaws are identified and useful options for further exploration suggested. We hope this will increase comparability among experiments, help less experienced scientists to prevent mistakes and essential omissions, and foster the advance of knowledge on non-chemical weed management.

2 General aspects

2.1 Experimental design

In designing any experiment there are a number of key steps. The first is to clearly identify the objectives of the experiment. These may be:

- to compare the efficacy of a number of different weed control tools or methods,
- to assess the effect of timing, dose or intensity on the efficacy of a method,
- to compare different combinations of methods.

The clear identification of the objective of the experiment will then aid the selection of appropriate treatments to be included in the experiment. Objectives of the first type will generally lead to the selection of qualitative treatments, for example different methods, probably with the inclusion of a control or standard treatment (e.g. un-weeded, hand-weeded, “industry” standard) with which the different treatments will be compared. Objectives of the second type will lead to the selection of quantitative treatments such as the timing of application, the number of applications or the intensity of application. Here it is important to select treatments that will cover the range of possible responses, probably including both a negative control (e.g. un-weeded) and a positive control (e.g. hand-weeded) to define the worst and best responses. Objectives of the third type suggest the use of some sort of factorial treatment structure, allowing the comparison of the different combinations of levels of each treatment factor. Treatment factors in such experiments might include both quantitative and qualitative treatments, and often an incomplete factorial structure might be necessary to incorporate appropriate controls or standards. Factorial structure provides the dual benefits of testing the effect of each treatment across a range of conditions (the level of the other treatment factors), whilst also allowing the identification of interactions between treatment factors.

Having identified the appropriate treatments and treatment structure, we can then identify the resources to be used. With glasshouse and laboratory experiments this is usually fairly straightforward – treatments will be applied to plants in pots or trays, and we just need to allow for possible sources of variability, such as position within the glasshouse in which plants are grown, and allocate plants to blocks appropriately. Unless there are very many treatments we will probably be able to have each treatment occurring just once in each block (e.g. using a randomised complete block design) so that the design and analysis will be relatively simple.

For field trials, we need to take account of any constraints on plot size and position within the field. Is there a minimum plot size that will be necessary for the realistic application of a treatment? This may differ between treatments, and may be much larger that it is realistic to assess, so that assessment will be of one or more sub-plots within each plot, or by selecting random or systematic quadrat positions. Both approaches have their place depending on what is being assessed – e.g. for intra-row cultivation it might be sensible to systematically position quadrats between rows, or to separately make within- and between-row assessments. Having selected the required plot size we then need to position the plots within the field. Are there features of the field that are likely to cause variability in the response? These might include the position relative to the field boundaries, slopes or the direction of prevailing winds, or even an observed variation in weed density or species composition. These sources of variation need to be accounted for in the blocking structure that is used. Note that blocks do not need to be contiguous – particularly where weed density is variable, it would be appropriate to allocate plots to blocks based on their weed density rather than their physical position.

For most experiments it will be most appropriate to use a randomised complete block design – that is a design where the number of plots per block is the same as the number of treatments, so that each block contains each treatment once. This may not be practical where there are a large number of treatments, in which cases an incomplete block design should be used, preferably a balanced incomplete block design to make the analysis as simple as possible. Other complications can include the need for two independent blocking structures. Where this is due to sources of field variability, a row-and-column design, such as a Latin square, should be used, though be aware of the constraints this may impose on the number of replicates. Two separate blocking structures can also be required in multi-factorial experiments where levels of one treatment factor need to be applied to much larger field areas than levels of the other factors. In such cases a split-plot type design would be appropriate. This type of design is often used inappropriately, where, for example, there is little interest in one factor (applied to main plots), to improve the precision of comparisons between treatment means for the other factors.

However, there are a number of disadvantages associated with using split-plot designs. The first is that by its nature, information in a split-plot design occurs at two levels, and the estimation of both error variances (residual mean squares) is on fewer degrees of freedom than would be available in the equivalent randomised complete block design – possibly requiring additional replication to have sufficient precision in the lowest stratum. Note that comparisons in the higher stratum will generally have poor precision because of the few residual degrees of freedom, and that this also impacts on the precision of some comparisons in interaction tables. A second disadvantage is that the loss in precision for the main-plot factors is much greater than the gain in precision for the sub-plot factors (based on a comparison of the expected mean squares for the two designs). A third disadvantage concerns the comparison of treatment means, and in particular those for the interaction between a main-plot factor and a sub-plot factor. Comparisons between interaction means with different levels of the main-plot factor will generally be less precise in the split-plot design than they would be in the equivalent randomised complete block design. A final disadvantage is the extra complexity involved in presenting tables of interaction means for split-plot designs, where it will generally be necessary to present two different SEDs, plus possibly SEDs for the main effects. Thus split-plot designs should only be used where necessary to allow sensible application of treatments.

Finally we reach the often difficult question of replication. Where information is available about the plot-to-plot variability (e.g. from previous similar experiments), and we know the size of difference that we would like to be able to detect as significant, then we can calculate an appropriate replication level. For most experiments we would recommend a minimum of three replicates, and a useful "rule of thumb" (based on critical values of the t-distribution) is to aim for between 12 and 20 residual degrees of freedom. Other issues include the replication levels used for control or standard treatments. Where many qualitative treatments are to be compared with these it is often beneficial to increase the replication to a level equal to approximately the square-root of the number of treatments.

Another replication issue concerns the decision about increasing the number of replicate or increasing the within-plot sample size of area to increase the precision of comparisons. The decision depends on the relationship between plot size and spatial variability within the experimental area. Where there is little spatial variability within each plot then increasing the number of replicates is the best approach. However, where the within-plot variability is high, the within-plot sample size or area needs to be increased to provide a representative measure of the treatment effect across the range of within-plot conditions. Where plot size is not constrained by physical requirements, it is sensible to fit the plot size to the scale of the spatial variability.

A final issue is the use of multi-site trials. These can be particularly useful in demonstrating the robustness of treatment differences or effects across a range of environments, and, if carefully designed, can usually be analysed together. This usually requires the use of identical designs (different randomisations) on each site. Where separate analyses of each site are not intended, the replication level within a site can often be reduced.

2.2 Assessing weed control

2.2.1 General overview

It may be useful to develop guidelines for the kinds of measurements to be used in different types of experiments, to allow a sensible comparison of results from different experiments. Assessments can be either done using quantitative methods (weed counts, weed biomass, weed seed production etc.) or qualitative methods (e.g. visual estimation of weed control). Where there are only a few dominant species, a count of the number of weeds in a given area may be possible. With many different species, an overall count will not take account of different sizes of plant, so that a total weed biomass may be more appropriate. Often, a combination of quantitative and qualitative measures are used. For example, the visual evaluations might be done early during the season while the crop and weed densities might be determined later at the end of the growing season or prior to crop harvest. Weed biomass along with crop yield might also be determined at harvest.

Quantitative measures are ideal since they give actually measured values of weed density or biomass at a given point in time. However, the cost in resources and time is often prohibitive and this is why experimenter will resort to qualitative measures such as visual evaluations to assess the effect of weed control treatments on weeds and on crops. Although countings seem accurate, they can be very imprecise if only few (<50) plants are found on a relatively small fraction of the plot area (i.e. within the quadrats, see 2.2.4 and Fig. 1). If visual classifications allow a larger area to be "sampled", the inaccuracy in assessing weed density may be partially compensated by lower sampling errors. If this trade-off is sufficiently large, visual classification might even have similar accuracy than countings. Whether to prefer qualitative or quantitative assessments is still subject to debate.

Whilst visual scores can be quicker and easier to collect, they will usually have the disadvantage of being less easy to analyse. In particular, if an overall score (say, on a 0–5 scale) of crop damage or weed control is obtained for each plot, such data will rarely satisfy the assumptions of any standard method of analysis. They will also rarely provide strong discrimination between treatments. Hence the choice of qualitative or quantitative measurements is the balance between the time and resources needed to make the assessment, and the ability to discriminate between treatments.

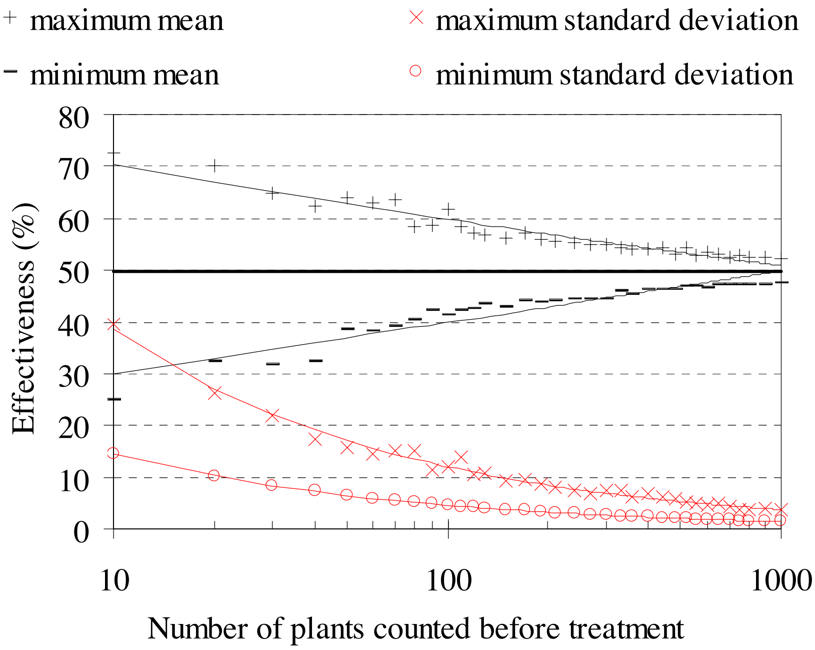

Figure 1. The effect of the number of plants per plot counted before treatment on the observed variability of the mean effectiveness (set mean =50%) and the standard error between the 4 repetitions. Binomial distribution, 500 virtual experiments per data point (Kurstjens, unpublished).

2.2.2 Visual evaluations

The following text has been partially adapted from an anonymous Canadian Weed Science Society document published in 1994 (Anonymous, 1994) and from Frans *et al.* (1986).

Visual assessments of the effect of weed control treatments on weeds can be used to complement weed counts or weed biomass sampling, or instead of these samplings. Visual observations can be taken very rapidly and more frequently than quantitative measures. In order to be reliable, these observations must be taken using a rating system that is clearly defined and simple. Weed scientists have developed several systems (Shaw and Swanson, 1952; Willard, 1958; Frans *et al.*, 1986; Gnegy, 1991; Anonymous, 1994). The most widely spread scale uses a 0 to 100 rating which is then used directly as percentages in analyses of variance (e.g. Table 1). The data might have to be transformed using the angular transformation (arcsin) in order to be normalized. However, if the scale is fairly crude (e.g. as percentage cover to the nearest 20%), data rarely satisfy the assumptions of analysis of variance (or other analysis methods), and will rarely discriminate between treatments.

There is some concern about the comment above relating to the use of a "0 to 100 rating scale". Analysis of such data as an arcsine transformed percentage is only really valid if the data are a proportion based on counts (e.g. the number of mini-squares in a quadrat that are filled by weeds). If it is purely a visual score then it may not have the appropriate properties for this transformation, particularly as the precision associated with particular scores will probably vary in an odd way with the mean score. There is also an issue with visually comparing treatments with the weedy or weed-free check plots. This is fine if all plots have the same initial weed density and composition, but in practise this is rarely the case. It is almost always better to take pre-treatment assessments and consider the post-treatment differences allowing for the pre-treatment variation. This again indicates the value of using a truly quantitative assessment, as using a pre-treatment score as a covariate will often have insufficient precision to discriminate between different levels of response.

Table 1. A linear rating scale that can be used to assess weed control or crop damage. (Modified from Frans *et al.*, 1986).

Rating	Weed Control	Crop Damage	Precision (%)
0	No weed control	No crop reduction or injury	2
10	Very poor weed control	Slight crop discoloration or stunting	5
20	Poor weed control	Some crop discoloration, stunting, or stunt loss	5
30	Poor to deficient weed control	Crop injury more pronounced, but not lasting	10
40	Deficient weed control	Moderate injury, crop usually recovers	10
50	Deficient to moderate weed control	Crop injury more lasting, recovery doubtful	10
60	Moderate weed control	Lasting crop injury, no recovery	10
70	Weed control somewhat less than satisfactory	Heavy crop injury and stand loss	10
80	Satisfactory to good weed control	Crop nearly destroyed - A few surviving plants	5
90	Very good to excellent weed control	Only occasional live crop plants left	5
100	Complete weed destruction	Complete crop destruction	2

It should be obvious that it is vital that all plots within an experiment are assessed in the same way and at the same time. Ideally, more than one person would rate each treatment and the average rating would be used. Where different assessors are to be used within an experiment, they should each be assigned to assess all plots within a block, so that any differences between assessors are accounted for by differences between the blocks, and do not affect the treatment effects.

The assessment of the weed control action of a treatment should be based on the comparison of the treated plots with the untreated control plots (weedy check). The aim is to assess as accurately as possible the decrease in biomass (i.e. number of plants, height, number of leaves, etc.) per weed species as compared to the check. The decrease in biomass is attributed to the action of the treatment. This reduction can be expressed using the rating system presented in Table 1 above. Weed control on paved areas (streets, walkways and other hard surfaces) can be assessed by visually rating the "picture quality" (Table 2 below). This reference scale is often used without comparison to a weedy check and thus serves as an absolute reference for "weediness".

Table 2. Picture quality classes for weed growth (Sluijsmans *et al.*, 1997).

Class	Weed growth	Description
I	none	no weeds
II	little	in places, no patches
II	moderate	Weed growth in many joints, in places patches
IV	heavy	Heavy weed growth in patches, no woody weeds
V	very heavy	Heavy weed growth in patches, including woody weeds

Without an exact count, there are limits to the accuracy of assessment even for the practiced eye. It has therefore been found useful to aim for a differentiation of approximately 2% exactitude in the extremes of the scale range, with a 5% to 10% accuracy in the rest of the scale (Anonymous, 1994). Similar observations have been reported in plant pathology (Horsfall & Barrat, 1945; Jenkins & Wehner, 1983). The precision of visual rating scales is generally believed to be variable within the scale with greater precision at the extremes and less in the mid-ranges (Horsfall & Barrat, 1945; Jenkins & Wehner, 1983). The use of the 0–100% biomass reduction assessment is no more or no less subjective than using any other scale (ie. 0–9 or 0–10), and the researcher's judgment still can be incorporated in the assessment.

If a particular weed is not uniformly present in the untreated control plots and is similarly non-uniformly distributed in the treated plots, then it must not be evaluated. If, on the other hand, a weed is not present in the untreated control plots but does appear in the treated plots, it must be classified as "not controlled" (i.e. 0% control). Some additional guidelines are (Anonymous, 1994):

1. First inspect all the untreated control plots (weedy check) and observe which weeds are uniformly and frequently present.
2. Decide which of the regularly present weed species correspond to the objective of the experiment.
3. Assess the effect (biomass reduction) of the treatment on each individual species of weeds to be monitored when compared to the control treatment and record as a percentage number. Do not rate minor infestations or non-uniformly distributed weeds when making a systematic analysis. Make note of any additional observed effects (e.g. suppression of weeds rather than total kill, potential for regrowth, uprooting, patchy control, etc.).
4. To have a clear view of the weed pressures at each site, one should characterize the weed infestation in the untreated control plots. Provide an estimate of the soil coverage by total weed infestation as a percentage. Determine the development stage (BBCH scale: Meier 1997) and density (number of plants per m^2) of the weed species to be monitored. This can be expressed as a percentage of the total weed infestation.

It must be recognized that a visual assessment does not represent an actual count. If actual counts are done, then the ratings should be expressed as number of plants per m^2, which can then be converted as a percent of the total weed density or as a percent of the weed-infested control. Assessment of percentage cover can be made more precise, for example by counting “weed-filled” squares within a quadrat, giving a value to the nearest 1%, and this is then more useful.

2.2.3 Weed sampling

Weeds are generally sampled using quadrats and this topic is abundantly covered in ecology and vegetation textbooks (e.g. Kent & Coker, 1992).

There are two broad approaches to sampling weeds in the field that will be discussed in this text: permanent quadrat or randomly placed quadrats. A quadrat is an open frame (wooden or metallic) that is placed in the field and where weeds are sampled (counted, harvested, etc). A permanent quadrat is one which is established when the plots are laid out in the field. Its location is randomly chosen but it is marked in order to ensure that subsequent measures are always taken at the same place during the growing season. This avoids sampling errors induced by spatial heterogeneity. A randomly placed quadrat is one that is placed immediately prior to a sampling and usually this section of a plot is not sampled again.

On paved areas, such as streets and walkways, weeds grow in joints between stones or pavers. The total joint length within a 0.25 or 1 m^2 quadrat can be calculated from the stone or paver dimensions. Measuring the joint length covered by weeds and dividing that by the total joint length within the quadrat yields a reliable estimate of weed cover on paved areas.

Typically, quadrats are of a rectangular shape in fields where the crops have been seeded in rows. Again, depending on the objectives of the experiment, the quadrat can be placed intra-row or perpendicular to the crop row. In very narrow crop rows when blind harrowing is used (flex-tine in cereals, for example), a quadrat might be placed perpendicularly to the crop row and include several rows. When inter-row cultivation is used alone or combined with intra-row tools, weeding effectiveness within and between the rows can differ considerably. In such cases, these areas should preferably be assessed separately. If the effectiveness of intra-row tools such as torsion weeders and finger weeders is of interest, the quadrats will be placed on the intra-row only, parallel to the crop row. The quadrat width should preferably correspond to the area not cultivated by the inter-row tools (i.e. 5 to 15 cm).

As variations in light and soil conditions differ between the intra-row and inter-row area, which may lead to difference in conditions for weed emergence and growth, the untreated control for intra-row weeding effectiveness should also be an intra-row area. This can be an inter-row cultivated plot, with for example 10 cm between the protecting discs of the row crop cultivator, so that intra-row effects are minimized. This inter-row treatment should be made similar in all plots, including the untreated control, in case there is some additional intra-row effect.

Quadrats should be sufficiently long to ensure that weed density is satisfactory in the weedy check (see 2.2.4). Note that the number of quadrats could also be increased to increase the number of weeds counted per plot. An increase in the number of quadrats, rather than an increase in the quadrat size, can improve sampling accuracy, especially with weed populations that are inherently variable as demonstrated by Lemieux *et al.* (1992) in sampling populations of *Elymus repens*.

The weeds in the quadrats could be sampled according to broad categories (monocotyledonous and dicotyledonous) or other categories such as perennial and annual, or could be sampled by species, and even by growth stage within a species. Such distinctions are only sensible if sufficient numbers are present for each class.

2.2.4 The number of plants to be counted

The number of plants to be counted on each plot depends on the variability of the weeding operation itself (e.g. working depth, steering precision) and its effectiveness, and the aspired accuracy. Ideally, treatment differences of 3–5% crop plant loss and 5–10% weed control effectiveness should have a fairly high chance (say 80%) of being detected at a 95% confidence level. The number of plants could be calculated from information on the magnitude and type of variation (i.e. the type of distribution that best describes the errors, e.g. a normal, lognormal, poisson or binomial distribution). However, in most field experiments, a previously fixed number of (generally 1–4 50×50 cm) quadrats per plot are counted, without knowledge on the actual weed density and its spatial variability at that time and location.

If the percentage (weed) control or (crop) plant loss are assessed by counting plants in permanent quadrats before and after treatment, the number of plants per plot can be estimated by a randomiser with a binomial distribution and a set probability (i.e. effectiveness) and number of units (i.e. plants before treatment). With 50% effectiveness, this would resemble repeated "coin tossing".

Table 3 and Fig. 1 show results from a simulation study based on 500 virtual experiments with 4 repetitions of two treatments with a preset difference in plant loss. Based on simulations with different preset differences, counting 100 weeds and 180 crop plants per plot before treatment is a reasonable guideline (Table 3). Counting less weeds would increase the probability of finding a significant effect that does not really exist (i.e. if the estimated variance is accidentally low). The probability of not detecting a significant effect increases as well. The observed variation between the repetitions decreases as the number of plants counted increases (Fig. 1). As the number of weeds counted is generally lower, often even below 50, it can be questioned whether the variable effectiveness of mechanical weeding can be attributed to the weeding technique or to inaccurate assessments. Trying to distinguish species-specific effects with such low numbers will rarely be sensible, even if the effects found are (accidentally) significant. For example, in very low density situations, a natural variability of 1 or 2 weeds might mean a 25 or 50% increase in an average population of 4 weeds.

Table 3. The number of plants per plot to be counted before treatment to significantly (P < 0.05) assess treatment differences in plant loss by t-test in experiments with 4 repetitions. Simulations with Genstat 5, a binomial distribution and 500 virtual experiments, using two references: 50% (weed) control and 0.1% (crop) plant loss (Kurstjens, unpublished).

effectiveness		Probability of significance	
reference	difference	50 %	80 %
50 %	5 %	180	460
	7,5%	75	180
	10 %	45	100
	15 %	20	40
0 %	1 %	275	460
	3 %	180	400
	5 %	180	400

It is not clear whether the level of variability simulated by the randomiser adequately represents the variability of weeder effectiveness in real fields. The values in Table 3 might be too low, because simulation did not account for spatially heterogeneous weed infestations and variability of weeder performance itself. Particularly if weed density before treatment is estimated from weedy checks, guidelines from Table 3 may be far too low because weed infestations are spatially heterogeneous, even within short distances (metres). This is just an example of the approach that might be taken to calculating sensible sample sizes. The numbers given are under a particular set of assumptions, and therefore shouldn't be taken as a fixed answer for all situations. A similar approach could be taken for other sets of assumptions.

2.2.5 Dealing with spatial heterogeneity

It should be pointed out that a basic assumption in our experimental layouts and statistical analysis is rarely met, as homogeneous weed densities are rather exceptional. Assuming weed distribution to be continuously variable seems more realistic. Experimental layouts that minimise the impact of weed heterogeneity and allow statistical discrimination of treatment effects from spatial patterns need to be developed. Further discussion and research in this area is definitely required.

Where a intra-row cultivation treatment is applied it may be appropriate to assess weeds between and within rows separately. Otherwise you need to take sufficient samples (see above) to have a representative measure of the within-plot variability (both natural and as caused by any treatment).

2.3 Assessing crop damage

2.3.1 Visual evaluation of crop tolerance

The same basic principles in weed assessments apply to crop tolerance assessment. In this case, however, the control treatment should be an untreated treatment kept weed-free by hand (weed-free check). Herbicides should not be used due to the possibility of confounding the results. Evaluations should be done with a comparison to this weed-free check.

Details of the rating scale are presented in Table 1. Inclusion of decimal values is inappropriate. Use whole numbers only to report. Initial damage of up to 10% will generally be outgrown and will disappear with time. The impact of these low levels of injury are generally not reflected in yield losses. More severe injury, however, will almost always result in yield losses unless the suppression of a dense weed population can compensate for such damage. The observed damage should also be described (i.e. stunting, broken leaves or stems, uprooting, bent stems, etc.). Yield determinations are a critical component of tolerance trials (Anonymous, 1994).

2.3.2 Crop sampling

The most obvious crop variable to sample is the commercial yield (quantity and quality). However, other data should be collected both prior to and after the treatments to better document the crop response. The same sampling techniques and the same times that were presented above can be used for sampling the crops. However, for crops that do not produce tillers, the quadrats can become simple lengths of crop rows. Again, the length used should insure that there is a sufficient density of crop plants to be able to do meaningful statistical analyses. In general, 30 to 75% of the crop rows within the plot could be sampled (excluding the guard space or guard rows), depending on the plot size and on the crop density. The variables measured could be: number of seeds pulled out of the ground, number of seedlings uprooted, number of plants left standing after a treatment, number of plants bent, broken, number of leaves damaged, crop growth stage at different dates, etc.

2.4 Assessment timing and frequency

Weed control efficacy evaluations and crop tolerance evaluations could be conducted prior to a treatment and 7, 14, 21, 28 and 42 days after the treatment and at harvest. The frequency and intensity of sampling will vary according to the objectives of a given experiment.

Where the natural weed flora is being assessed, and where there is substantial plot-to-plot variability prior to treatment application, it may be useful to take a pre-treatment assessment to be used as a covariate in any analysis.

The timing of weed counting may have a strong effect on the results (see Fig. 2). Using fixed spots for successive weed countings should reduce random variation. Assess the situation prior to weed control treatment to see the initial situation, so you can measure the change due to control treatment, and use the initial situation as a covariate in statistical analyses.

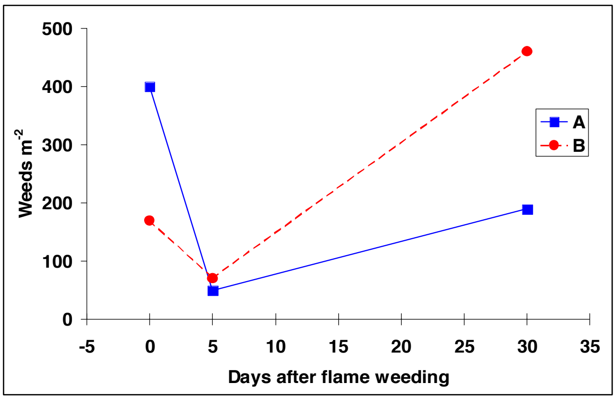

Figure 2. An example of three different weed assessments: Immediately before weed control treatment, and 5 days and 30 days after treatments A and B (modified from Vanhala, 2000). The results and their interpretation may strongly depend on which of these assessments are done.

Generally the weeds are counted after treatment only once. The time depends on whether competition and new emergence effects should be included, and whether the combined effect of treatments involving multiple weedings would be of interest. An open question still is: how many days does it take for weeds and crops to recover? To distinguish between the effectiveness on white threads and emerged weeds, and to account for new weed emergence, permanent quadrats that are (accurately) hand weeded just before treatment can be included on treated and untreated plots. All permanent quadrats (both weeded and not weeded) are counted just before the subsequent treatment. Weed counts from previously weeded quadrats indicate new emergence, that can be used to correct counts from non-weeded quadrats. Spatial heterogeneity and quadrat size are important considerations in quadrat layout within the plots. Collecting, washing and weighing plants from the previously weeded quadrats provides information on cultivation timeliness. Principally, it is possible to assess growth reduction of surviving weeds. However, spatial variability and low weed densities limit the achievable precision considerably.

2.5 Analysis

For any designed experiment, it will usually be sensible to use analysis of variance to provide an initial analysis of the data. For a well-designed experiment this should be simple in most statistical packages. Some measured variables will require transformation prior to analysis – counts often require a square-root transformation, proportion based on counts require an arcsine transformation, and weights can require a log transformation. An alternative approach for counts and proportions based on counts is to use a generalised linear model (GLM) analysis assuming a Poisson or binomial distribution, respectively.

Another area of concern is the transformation of responses to a percentage of the weedy check. It is important to analyse data in such a way that the plot-to-plot variability in these treatments is included, and not to convert data to percentages prior to analysis. If required it is relatively easy to convert the treatment means produced by an analysis to percentages of the weedy check, with the added advantage of having an SED to assess whether the difference is important. Converting the data prior to analysis will deflate the residual mean square, resulting in differences appearing more significant than they should be.

If all treatment factors are qualitative, then the analysis of variance may be all that is needed. Paying careful attention to the treatment structure can help in the interpretation of the response, and it may be helpful to partition treatment sums of squares into single degree-of-freedom contrasts to address specific questions or comparisons. Where control or standards have been included it will often be most appropriate to compare all the other treatments with these, rather than with each other. Where a factorial treatment structure has been used, then use this structure to interpret the results, first considering the main effects, then two-factor interactions (where these are large compared with the main effects), and so on.

Where treatments are quantitative some form of regression analysis may be appropriate. Both linear and non-linear regression approaches may be useful. Linear (polynomial) regression is limited to providing a simple description of the shape of the response. The choice of an appropriate non-linear response function (based on previous experience or plotting of the data) will allow a more detailed interpretation of the response. Even more complex models could be developed based on knowledge of the mechanisms involved. Where both qualitative and quantitative factors are included, a parallel regression approach will be appropriate, allowing parameters of the regression models to vary with the different levels of the qualitative factors.

Of course efficacy of weed control may not be the only measure of interest. It may be important to assess the effects of treatments on the crop (harvest yield or assessments during crop growth), soil structure, N-mineralisation, etc., or to assess the cost of applying the treatment in terms of energy or time required per unit area. Often there will be multiple responses of interest, and some form of multivariate analysis might be appropriate, or a combined measure of treatment effect might be calculated. Multivariate analysis of variance can be used to assess for treatment effects in the same way as univariate ANOVA, though it is often difficult to interpret the effects. Most other methods (e.g. principal component analysis or cluster analysis) are purely descriptive, though discriminant analysis can be used to identify the variables that contribute most to differences between treatments.

Presentation of the results of any experiment should include a full description of:

- the experimental design, including the type of design used, replication level, treatment structure, and level of each treatment factor,
- the measurements taken, including any calculations or transformations performed prior to analysis,
- the methods of analysis used, including references where the method is not standard, and indicating any important assumptions made.

Where treatment means are presented, these should always be accompanied by standard errors of differences (SEDs) or LSDs (usually more appropriate than standard errors of means, as we are interested in comparing treatments). Where regression analyses are used, a graphical display of the observed data and fitted lines is usually valuable, along with details of parameter values (and their standard errors). Where SEDs, LSDs or standard errors are presented, the residual degrees of freedom on which they are based (and significance levels for LSDs) should also be presented. However, the required practice in reporting statistics may vary between journals.

2.6 Describing the experiment

2.6.1 Site and experimental conditions

A basic thing in reporting is to tell when and where the experiment was conducted.

Describe the following weather conditions in open field, both during the treatment and during the whole experiment: temperature (also max and min), quantity of water (rain or irrigation). In controlled conditions describe all the climate parameters that is possible to measure. Record the time of the day when the treatments were done (relevant for soil moisture and plant turgidity). In many cases it is relevant to describe whether there was dew or other moisture on weeds and crop plants, as well as the velocity and direction of wind (e.g. in relation to burners in flame weeding).

Soil type (Anonymous, undated a), moisture and fertility may considerably affect the plant condition, effect of treatments and survival of weeds and crops. Therefore it is essential to record at least the soil type, soil moisture (see e.g. Klocke & Fischbach, 1998), condition of the surface (roughness, unevenness) and amount of (soluble) nitrogen given in fertilization. To be more specific, the authors may describe soil physical and mechanical characteristics: texture, classification (ISSS or USDA), Atterberg limits, soil water content, dry bulk density, cone resistance, and others characteristics (see Anonymous, 2001) that they consider useful to describe their trial. This soil characterization is particularly useful for experiments that involve the interaction of implements with the soil. Some of them – soil water content, dry bulk density, cone resistance – should be assessed immediately prior to the treatments.

2.6.2 Machines and adjustments

The first step should be to identify the manufacturer of the equipment used and the model number or name. Also, the year of manufacture should be included if known because some models are modified or stop being manufactured after some time. The overall dimensions of the equipment and the modifications made to it should be also reported. A small multi-language glossary of cultivators and other implements that are used in physical weed control is available at the web site of EWRS Working Group Physical and Cultural Weed Control (Anonymous, undated b).

The proper adjustment of a tool is often more important than the choice of tool. Therefore it is of little information just to mention that you used this or that tool without saying anything of the adjustment and way of working. It is like saying I used a Hardi sprayer, and tell nothing about the herbicide, dose or spray volume.

Where there are no standard methods to describe the adjustments and mode of action (please find more specific information in section 3 and 4), at least try to describe the work the tool did, including all parameters that could be of relevance (e.g. driving speed, working depth, tine angle, distance to the row). Factors that do not affect weeding effectiveness or crop growth per se might also be of interest (to others, later), such as the effective, accessory and operative time (to calculate working capacity, fuel consumption per hectare and hour), the drawbar pull or p.t.o. torque and rpm. Using parameters such as useful power and wheel slip of the tractor is not recommended as they depend on other factors as well (e.g. tractor weight, tire size and inflation pressure, engine and transmission efficiency) and therefore may not be representative. Also direct energy or/and total input can be useful when different weed control techniques are confronted (with different machines, fertilization, etc.).

2.6.3 Weeds and crops

When describing the weeds and crops, one should list the crops or/and the (most abundantly present) weed species involved (identify them using Latin names and report the names of the cultivars used along with the crop names) and the cultural practises. For weeds (and preferably for crops, too) their density and growth stages at the time of treatment should be given. The BBCH scale (Meier 1997) is a good reference point for people to be talking uniformly about the same growth stage of a weed or a crop. Any abnormalities (like plant diseases) should be recorded.

3 Thermal weed control

In thermal weed control, weeds are heated in order to kill them or at least reduce their competitive ability. There are three main categories which determine the result: technological, biological and environmental factors. Technological factors are e.g. heat transfering medium (flame, hot water, steam, e.g.) the fuel, properties and adjustments of the equipment, driving speed and the uniformity of the heat transfer rate across the working width. Biological factors include: plant species, developmental stage, plant density etc. Plant species and developmental stage determine the location of sensitive parts of the plant and how well they are protected. Environmental factors such as wind, rain, dew, cloddishness of soil may affect burner function, heat transfer etc. These factors should be recorded and their effect on the experimental results considered. Each of them may be a subject of research.

A necessary prerequisite for the development of experimental designs or the interpretation of experimental results is the knowledge about the thermodynamic principles. To kill off a plant it is necessary to heat up the essential parts up to a lethal temperature. The essential part of a plant is depending on plant kind and growing stage (Bertram, 1993, 1996, 1997, 2001, 2002a).

The task of the weeder is to transfer the necessary energy to the surface of the plant. The heat transfer to the plant surface can take place by convection, radiation, condensation or by conduction (Fig. 3). For this purpose, different technical solutions (flame, hot water, steam, heat radiation) had been developed. Within the plant tissue, the heat transfer takes place only by conduction. In general, the heat transfer rate from the plant surface to the inner parts by conduction is very low compared with the heat transfer rate to the plant surface. This means that all plant parts (leave, stem, vegetative point) must be heated for a sufficient period of time.

The paper focus on flame weeding. For evaluating other or comparing different types of thermal weeders the presented hints and research methods can be also very useful.

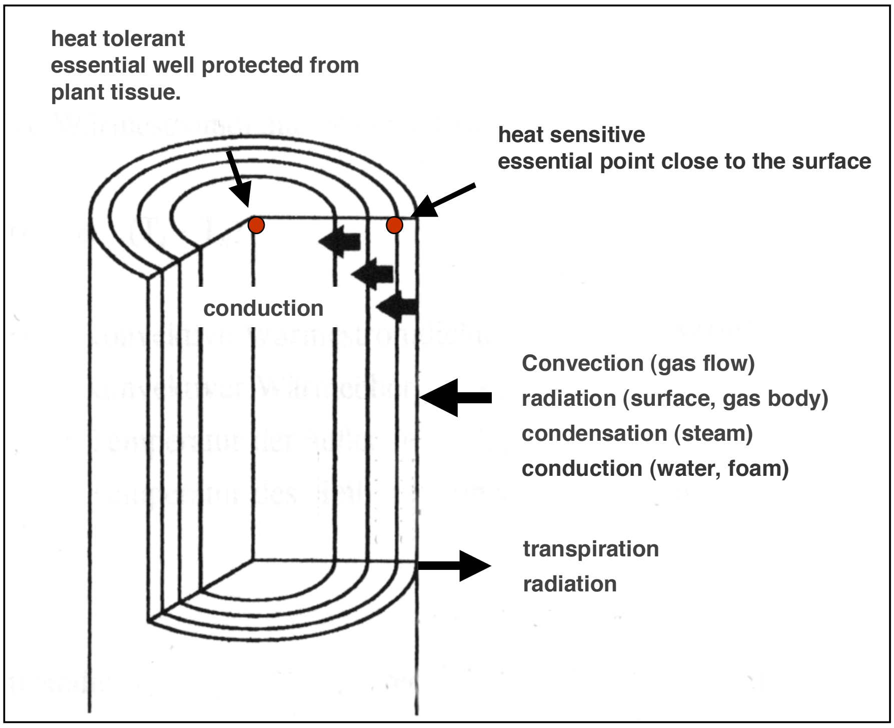

Figure 3. Heat transfer mechanism in thermal weed control and model of a heat tolerant and a heat sensitive plant (Bertram 1996, 1997, 2001, 2002a).

3.1 Experimental set-up

Applied field research aiming at evaluating proper strategies for weed control should be performed in real life in fields with real crops and weeds. However, when the aim is to compare e.g. two flamers or to evaluate the optimal adjustments of a flamer, there are clear advantages of using standardised test methods using homogenous stands with test plants of e.g. *Sinapis alba* (see e.g. Ascard, 1994, 1997, 1998). It is important to keep in mind that the plants still have to be treated in the right stage, e.g. the optimal settings and dose needed for relative large test plants (2–4 leaves) are not the same as for treating susceptible weeds in the cotyledon stage.

In flame weeding research, the flame treatments are often compared at a few pre-set intensity levels, often quantified by e.g. the travel speed or the fuel pressure. When the effects of such treatments are compared by analysis of variance, a qualitative assessment is performed to see whether one treatment is significantly different from the other. This kind of qualitative assessment is, however, often not relevant when treatments are compared with highly different energy inputs.

The most suitable way of quantifying the lethal dose is choosing a dose-response (or speed-response) experimental set-up. In herbicide research this kind of bioassay has been developed and widely used by Streibig *et al.* (1993). Dose-response and speed response models for flame weeding have been developed by Ascard (1994, 1995, 1997, 1998) and also used by e.g. Bertram (1996, 2002b) and Hansson & Ascard (2002). The main advantage of this quantitative approach is that comparisons between machines and adjustments can be made at a fixed effectiveness level (e.g. 50% or 95% biomass reduction). As it is difficult to accurately estimate the final effect from visual assessments directly after treatment, dose-response experiments provide more accurate values of the lethal dose.

Generally five speeds in the range 10–90% weed reduction (plus an untreated control, and a very high dose giving maximum reduction), are necessary to establish a complete dose-response or speed response curve, which adjacent speeds differing a factor 1.3–1.7 (e.g. 1.0, 1.5, 2.25, … km/h). The smaller the factor, the more accurate effective doses can be estimated. If weeds are likely to recover (e.g. grasses), including a very high dose (>500 kg LPG/ha) and manually clipping at the soil surface at treatment provide useful reference plots.

To set the speed range, operate the machines outside the plots at various speeds. The lowest speed should certainly kill all plants, whereas the highest speed should yield a growth reduction of less than 40% (Fig. 4). It is recommendable to calibrate tractor speeds at different gears at 2000 engine rpm in advance, so that adequate gears and engine speeds can be selected after the desired speed range is defined (palmtop computer is handy here). If machines have a variable transmission, record the speeds on all plots.

Figure 4. Direct effects of flaming at the early 2-leaf stage (top) and the late 4-leaf stage (bottom) of *Sinapis alba*. Untreated (left), lethal damage (middle) and mild growth reduction (right) (photos: D. Kurstjens).

3.2 How to perform the treatments

As compaction can induce large variability within the population and across the experimental field (also with *Sinapis alba*), wheel tracks created by seedbed preparation, sowing and treatments should preferably be matched and excessive rolling prevented. For *Sinapis alba*, a sowing density of about 15 kg/ha in rows spaced 10 cm and a plant density of about 250 plants per m² is common. It is recommendable to plan 25–40% extra space to be able to leave out irregular plots and provide space for adjusting implement speed.

3.3 Describing the equipment and adjustments

There are few standard burners today. Therefore you have to describe as carefully as possible, the brand of the burner, any serial number or model, the nozzle size, number of nozzles per m burner width, the fuel (e.g. propane), gas phase or liquid phase burner, flame temperature or the gas:air ratio, the place where gas and air are mixed, natural or forced air supply, etc. Any burner cover should be described, e.g. the length and the height in the forward and rear end. Also measure the width and height of the open area at the front side of the flamer, through which cold air enters under the cover. A picture/drawing often says more than thousand words, and a measuring scale can then replace a lot of figures. Please also describe the flame length and the height of the burner above ground, and the angle, and specify which angle you mean (Fig. 5).

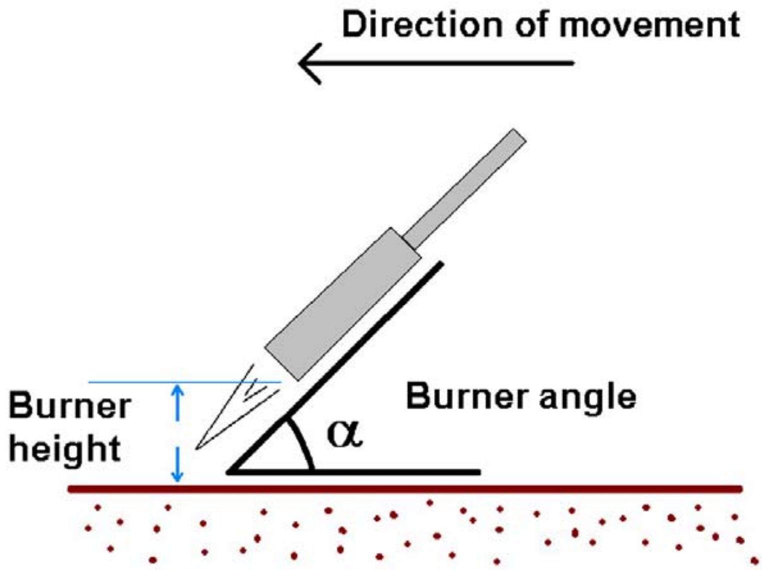

Figure 5. The angle of burner in relation to driving direction should be recorded, as well as the height of the lower part of the burner above ground. The angle may be given relative to the horizontal ground (downward directed burner would be 90°) as in the picture, or relative to the vertical (downward directed burner would be 0°), but this should be stated clearly (Vanhala, unpublished).

Very useful information is the LPG consumption in kg h^{-1}. If several burners are mounted on a flamer, please give also the burner power in kg h^{-1} per metre working width, since this measure is very valuable in comparing the burner power of different flamers and also in calculating the gas consumption per hectare. See examples in Ascard (1994, 1995, 1997, 1998), Peruzzi *et al.* (2000) and Raffaelli *et al.* (2002). The LPG (propane) consumption MUST be determined by the researcher in separate repeated tests, by weighing of propane tanks before and after each test, with the actual flamer unit. Never trust gas consumption given by the company. Never just calculate the consumption using a formula with nozzle size and gas pressure. The difference in reality may by surprising. Nor can you count on gas pressure values given by a non-calibrated manometer (pressure gauge).

If the experiment compares different flaming intensities, state if the LPG dose was regulated by the driving speed, the gas pressure or both. Give the dose in kg LPG ha^{-1} treated area. This means that if you are doing banded treatment in 10 cm strips in the rows using a dose of 50 kg ha^{-1} per treated area, and the row spacing is 50 cm, then the gas consumption is 10 kg ha^{-1} per cultivated area. The energy input can also be given in e.g. MJ ha^{-1}, but please then state the conversion factor used. The intensity can also be described by giving the driving speed, but remember always stating the dose also in kg ha^{-1}, since the driving speed itself is not relevant if you use flamers with different energy input.

3.4 Assessing plant response

3.4.1 What to assess?

Temperature measurements with a defined measuring body can be helpful for a rough estimation of a system. But the proposed measuring body is not a plant model. For killing off a given plant (species, growing stage) it is necessary to measure the necessary amount of energy which has to be transferred. Only the speed/dose response relationship is suitable for this purpose.

Common response parameters are plant density and the oven-dry plant weight per square metre. The fresh weight is a less reliable parameter, as water content depends on growth stage and environmental conditions. If it rains between treatment and clipping, considerable amounts of soil can splash onto the plants. After rinsing off the soil, drying to constant weight at 65°C should be done rapidly to prevent rotting, using a ventilated oven and preventing compression of plant material. Try to prevent slow drying when the material is too massive or compressed. The material could be turned around within pots, quickly pre-dried in direct sunlight in a ventilated space, or placed in a very thoroughly ventilated stove. Harvest at least 40 plants (if present) from each of two random but representative locations within a plot, recording the number of plants and the harvested area (minimum 0.25 m^2 each, up to 10 m^2 in highly effective treatments). If surviving plants contain a significant amount of dry dead material, it is possible to derive the alive dry mass from the fresh weight and the dry matter content of undamaged plants and plant material according to the following formula:

ADW=(MFW*DMD*DMU-MDW*DMU)/(DMD-DMU)
where
MFW= net measured fresh plant weight
MDW= net measured dry plant weight
DDW= net dry weight of dead material in MDW
ADW= net dry weight of alive material in MDW
DMD= dry matter content of dead material (=net dry weight / net fresh weight)
DMU= dry matter content of untreated plants (=net dry weight / net fresh weight)

Assessing plant density and plant weight at the time of treatment is not common. However, it is very helpful in comparing between experiments (e.g. the dose required to reduce dry plant mass after 14 days to the same level that the mass was at treatment time).

If experiments are conducted on weeds that have a high probability of recovery (e.g. grasses), the effect can be assessed by clipping at least two times 1.5 m rows on fields plots, or by visual assessment (both on fields plots and paved area). Defining a common and clear assessment scale (e.g. Table 2), training the assessors before judging the treatments by at least two persons independently, and withholding information on the treatments applied from the assessors enables reliable classification.

3.4.2 Time of assessments

The time of assessment depends on the purpose of the treatment. When flame treatment is carried out pre-emergence of the crop, the aim is to reach a complete kill of young weed seedlings. Then the counting of weeds that survived is relevant soon after the wilting of treated weeds, when it is clear if the treated weeds will survive or not.

When you flame the weeds pre-emergence of the crop, and then count the weeds some time afterwards, you will have a mixture of treated weeds that emerged before the treatment and newly emerged weeds that emerged after the treatment. This means that even if the flame treatment gave 100% control of emerged weeds, a weed count some weeks later may indicate that the weed reduction was much less (Fig. 2). The longer you wait, the lower the final weed reduction will be. In applied research the most relevant time for assessment is just before hand weeding, which is the measure relevant for the grower who has to hand weed the remaining weeds.

However, if you want to estimate the optimal dose for achieving near 100% control of emerged weeds, you will have to count the weeds both before and after the treatment. Do not wait until all weeds have emerged because then many weeds have grown beyond the cotyledon stage, when the treatment is normally done (or at least should be done), and then you will need a greater energy input.

Assessing the effect of flame weeding should be performed when the treated plants and leaves have wilted and it is clear if a plant will survive or not. In the field, this may take from a 3–4 days up to 1–2 weeks depending on the conditions. One way is to wait until surviving plants show a little regrowth. If you treat weeds with protected growth points or perennial weeds that will always survive and regrow after treatment, weed counts only is less valuable, and you then have to estimate the weed cover or weed weight.

If you are doing repeated flame treatments on e.g. weeds in urban areas or in orchards, one relevant question is how many treatments per year are required to obtain a desired control level. If so, one has to decide a certain weed stage when the next treatment should be done. If weeds recover, estimating the number of days required for the original weed infestation level to recover seems more relevant than estimating the growth reduction at a certain time *per se*. In this case a rough guideline for the time between treatment and assessment is 14 days, but this may vary considerably depending on geographical location and weather conditions etc. As plant surface should be dry at harvest, such a guideline would only be approximate. To assess the recovery time, multiple assessments should be done from one week after treatment onwards in weekly intervals.

3.4.3 Temperature measurements

Temperature measurements using thermocouples are of little use for evaluation of flame weeding, if not complemented with evaluations on weeds in relevant stages and growing conditions. The fundamental problem of using thermocouples to predict the weed control of a thermal treatment is that weed control depends on the effected temperature in the plant tissue and not on the temperature of the flowing medium. For example, steam or steam/air mixtures are effective at a lower temperature because the heat transfer takes place mainly by condensation (Bertram, 2001).

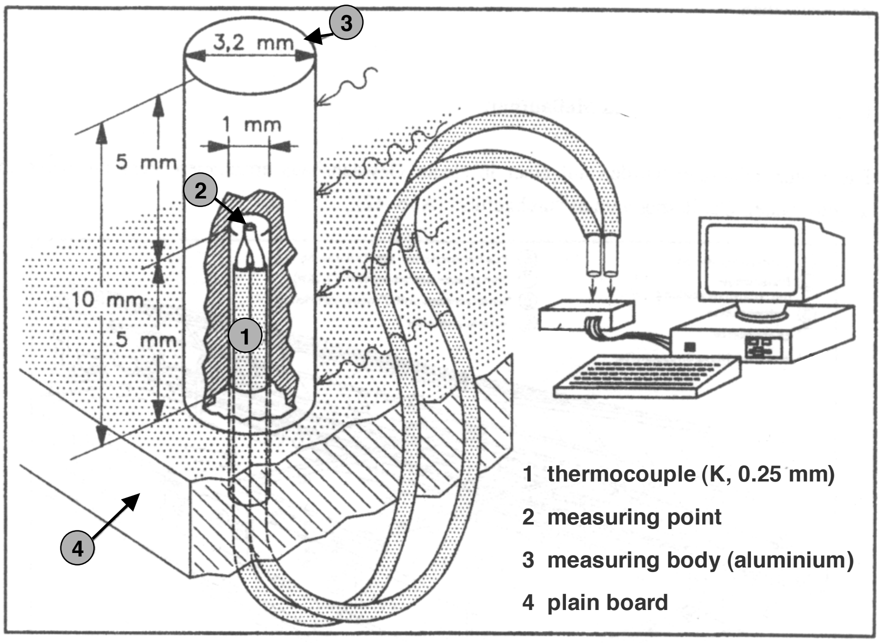

Figure 6. Standardized measuring body for evaluating heat transfer in thermal weed control (Bertram 1996, 2001).

The temperature increase of a bare thermocouple and a given thermal treatment depends additionally on the size of the thermocouple. The reaction time of thin thermocouples is faster than the reaction time of thick thermocouples. For a good temperature measurement, it is necessary that the measuring point of the thermocouple quickly reaches the temperature of the evaluated medium. For evaluating the heat transfer rate, it is necessary to do the opposite. A measuring body, which covers the thermocouple, reduces the temperature increase during the thermal treatment (Fig. 6) (Bertram, 1996, 1997, 2001, 2002a). The proposed measuring body leads to a temperature increase for a successful weed control of small plants (pre emergence flaming) of around 20–60 K and a transferred energy of 3.7 J – 11.2 J. From the thermodynamic point of view there is a need for the standardization of size, material and location (height over ground) of the measuring body (Bertram, 1996, 2001, 2002).

If temperature measurements are used they must be performed on dynamic flamers, not on stationary flamers. The choice of thermocouple highly influence the response and maximum temperature obtained, as shown by Ascard (1997: fig. 9). Therefore the type of thermocouple, the size of the wire and the welded conjunction point should be given, in order to be able to evaluate and repeat the experiments. Alternatively, one could derive the environment temperature by measuring the step response of individual thermocouples (using a lighter, Fig. 7) and correct the recorded curves for the slow sensor response. There is usually a sigmoidal relationship between the recorded maximum temperature obtained from dynamic flamers in the laboratory, and the weed reduction in the field. This means that above a certain temperature there is a little increase in weed control (Ascard, 1997, 1998). There was a high correlation between temperature and weed reduction mainly in the sublethal flame treatments (say 20–80% weed reduction), that were of minor relevance for practical use.

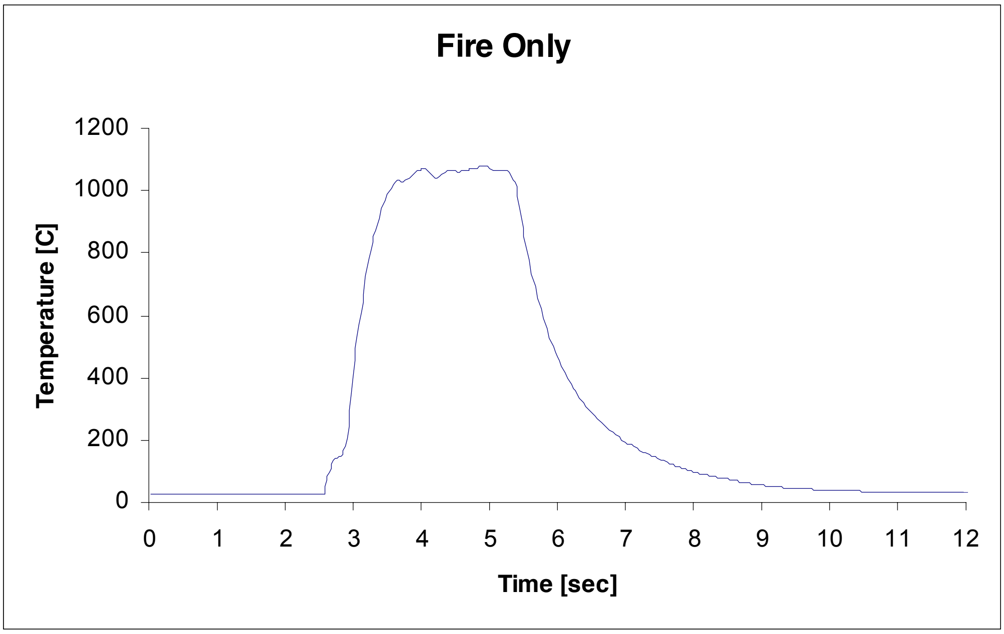

Figure 7. Measured temperature in the flame of a lighter, using a type K 0.127 mm chromel-alumel thermocouple with exposed junction (Omega Engineering, SPCH Chromel 0.005 inch chrome/nickel, SPAL-005 Alumel 0.005 inch Aluminium/nickel) (Dedousis, 2003).

The uniformity of the heat transfer across the working width and along the treated area is an important factor on the speed/dose response relationship. This uniformity is influenced by the weeder, the soil surface and the wind. Temperature measurements with measuring bodies can help in evaluating this influence on the results. For this task, temperature measurements are a smart method to get important information of the evaluated system without being labour-intensive (Bertram, 1996, 2002a).

4 Mechanical weeding – weed harrowing and intra-row cultivation

4.1 Introduction

Weeds can be controlled mechanically by a large variety of implements that cultivate on the crop row or on narrow strips close to the crop rows (intra-row weeders, e.g. finger weeders, torsion weeders, pressurised air, or powered vertical brushes), strips between crop rows (inter-row cultivation by e.g. steerage hoes, powered horizontal brushes, or S- or C-shanks with sweeps) or both (e.g. weed harrowing or rotary hoeing). Inter-row weeding is usually very effective and assessments are quite straightforward. The main challenge to both practical farmers and research is the selective control of weeds within the crop rows.

As there are limited possibilities to control weeds once they have escaped control (i.e. by herbicides or hand weeding), interactions between subsequent cultivations, interactions between cultivations and weather-, soil-, and species-related weed emergence flushes, and crop-weed interactions are very important. Pre-emergence harrowing is carried out after drilling but before crop emergence. The aim is to kill the first flush of emerging weeds and to give the crop an early advantage over the weeds. This may aid selectivity of subsequent weeding operations. The effect of pre-emergence harrowing is highly influenced by factors that affect weed and crop emergence. Post-emergence harrowing is carried out in early crop growth stages. The effect is mainly influenced by soil and weather conditions, weed species, and size characteristics of weeds and crops. Weed harrowing in late growth stages is occasionally called selective harrowing and may perform the functions of an inter-row cultivator if the crop has dense rows and clear size advantages over the weeds (Rasmussen & Svenningsen, 1995).

As weeds are highly sensitive in early growth stages, both pre- and post-emergence control efficacy are very time sensitive. Untimely weeding may cause the largest weeds to escape control. Particularly weeds that germinate early in the period between crop emergence (or earlier in the case of small-seeded shallowly-drilled crops) and the moment when the crop tolerates gentle cultivation may be difficult to control with the level of weeding aggressiveness tolerated by the crop. Thus, improving weeder selectivity, optimising cultivation aggressiveness and integration with other tactics that control these weeds (e.g. flaming at crop emergence), reduce or delay weed emergence (e.g. stale seedbeds, allelochemicals from compost and green manure, punch planting), or shorten or shift this critical period (e.g. transplanting, delayed drilling) are major research items. Before the crop becomes sensitive to pre-emergence weeding and after the crop rows are sufficiently dense and tall to withstand selective weeding, maximising weed control and increasing the size of weeds that can still be controlled by intensive disturbance and displacement of a preferably shallow topsoil layer is the main research objective.

4.2 Objectives and approaches

Depending on the research objectives, several experimental designs, measurement methods and approaches have been used. These objectives can be classified according to the sections below.

4.2.1 Comparing implement selectivity

Comparing different implements with respect to their selectivity and achievable range of aggressiveness in various crop and soil conditions contributes to optimising adjustments of single operations and selecting and innovating implements. To assist differences in selectivity, implements should be compared at the same level of weed control (this assessing differences in crop damage) or at the same level of crop damage (this assessing differences in weed control). As it is difficult to achieve this by repeatedly adjusting weeder performance (e.g. by working depth, driving speed, the number of passes or tine angle adjustment), quantitative approaches should be adopted in which each implement is operated at different levels of crop damage and associated weed control. The target range of aggressiveness is between 1% crop damage (gentle action) and 99% weed control (aggressive action)(Fig. 8). If crop damage equals 0%, a more aggressive action would increase weed control but might not necessarily cause more crop damage. Thus, unless adjustments reflect the maximum achievable aggressiveness under the present situation, their optimality cannot be judged. The same holds for the situation where 100% weed control is achieved, because crop damage might be reduced without compromising weed control. Assessing the relationship between weed control and crop damage over the full range of achievable aggressiveness is important to acquire information on the size of weeds that can still be controlled and the earliest crop growth stages allowing cultivation.

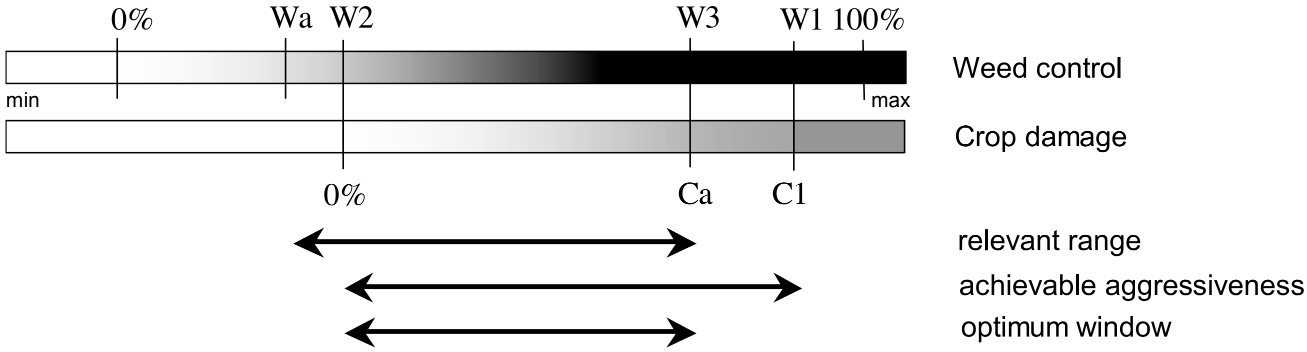

Figure 8. Hypothetical levels of weed control (top bar) and crop damage (lower bar) as related to weeding agressiveness (left = gentle, right = aggressive). Ca is the maximum acceptable crop damage, Wa the minimum acceptable weed control. W1, W2, W3 and C1, C3 represent the hypothetical weed and crop damage observed at various steps in the adjustment optimisation procedure (see text)(adapted from Kurstjens 1999).

Quantitative approaches are particularly important if weed and/or crop damage cannot be reliably assessed during treatment, or if the relevant parameters can only be assessed after a while, when damaged plants have either recovered or are killed. Rasmussen (1990; 1992) introduced a selectivity concept based on the relationship between weed control and crop soil cover, where weed control was assessed by density reduction 4–8 days after treatment and crop soil cover was assessed as the degree of soil covering of the crop immediately after harrowing. Although, this definition of selectivity only reflects the initial crop and weed responses and does not account for weed and crop recovery or further weed germination after harrowing, Rasmussen's work showed that selectivity always declines at increased levels of weed control. The same applies to intra-row weeders.

Analysing progressive series of cultivation aggressiveness by regression models (for relationships between weed control and crop damage or aggressiveness-response curves for single species) is valid if single cultivations are compared at identical conditions. As these empirical relationships are specific for the weed, crop and soil conditions present, an alternative modelling approach is being developed to distinguish between the selective ability of the weeder and the potential selectivity that can theoretically be achieved in specific crop-weed situations (Kurstjens *et al.*, 2004). Deriving the potential selectivity from crop and weed characteristics (e.g. anchorage force, plant height, plant flexibility) is required to adequately separate the effects of crop and weed size, soil conditions and implement adjustments. The dimensionless selectivity parameters for the crop-weed situation and the weeder-soil combination are intended to be independent of cultivation aggressiveness. If models simulating weed emergence and early growth could predict the crop-weed selectivity parameter, this approach could be used to optimise weed management scenarios (e.g. minimising weather dependence) and predict optimum timings and aggressiveness of consecutive weeding operations.

4.2.2 Comparing methods by single cultivations

In experiments without different levels of aggressiveness, each method (or weeder) should be used in an optimal way to adequately reflect their true potential. However, basic questions are: "what adjustment is optimal for the situation?" and "how can we achieve it?". This applies to experiments that compare different weeding methods (e.g. harrowing, hoeing and flaming), assess crop tolerance and weed control at various growth stages, or other experiments in which weeders are used at one single adjustment. In such experiments, it is important to describe when and how implements have been used and the assumption behind the treatments. Based on Fig. 8, a procedure to arrive at the optimum weeder aggressiveness can be devised (Kurstjens, 1999):

1. Use the most aggressive adjustment and assess the associated weed control W1 and crop damage C1. If crop damage equals 1% or less, the adjustment is optimal. However, if W1 < Wa (the minimum acceptable weed control level), the treatment is not efficient and should be reconsidered. Else, proceed to step 2.
2. Adjust the implement more gently, to achieve a crop damage level that can just be compensated (i.e. the most aggressive action that still causes no crop damage), and assess the associated weed control W2. If crop damage exceeds the acceptable level Ca, the cultivation should be postponed until the crop is less sensitive. If weed control equals 99% or more, or if the objective is to assess the achievable level of weed control without (expected!) crop damage, this is the optimum adjustment. To be able to check whether this adjustment causes no crop damage later on, describe the situation or take a picture. Else, proceed to step 3.
3. Increase weeder aggressiveness to achieve the maximum acceptable crop damage Ca and record the level of weed control W3. If W3 equals 99% or more, reduce the aggressiveness again to achieve just 99% weed control with minimum crop damage. Then record crop damage C3. If the objective is to minimize the number of cultivations and assess the crop damage associated to maximum weed control, this is the optimum adjustment. Else, proceed to step 4 to further reduce crop damage.
4. Choose an aggressiveness between the level at step 2 and 3. The window within which the compromise between weed control and crop damage is defined by (0, W2) on the "gentle" side and (W3, C3) on the "aggressive" side. Within this window, the economic optimum is at the aggressiveness where the expected incremental crop yield decrease (by increasing crop damage) equals the incremental decrease of additional weed control costs. Although this optimum can be calculated from the relationship between weed density and hand weeding costs, cultivation costs, and the relationship between crop damage and financial yield, the concepts developed by Kurstjens (1999) still need to be further elaborated and tested.

Understanding of the damaging mechanisms and qualitatively assessing the specific weaknesses of weeds and strengths of the crop (Fig. 9) could help in optimising weeder adjustments. Measuring crop and weed characteristics such as plant anchorage force, height and flexibility, could be helpful to characterise their susceptibility and predict the shape of relationships between weed control and crop damage (Kurstjens *et al.*, 2004), but is not practical for optimising implement adjustments in field experiments.

Crop and weed susceptibility characteristic	Relative advantage: weed		no difference		crop
Tall plant					X
Difficult to bend downward		X			
Strong anchorage in topsoil			X		
Strong anchorage in deeper layer	X				
…					

Figure 9. Assessment schedule for weed and crop characteristics that determine their relative sensitivity to mechanical damage, with scores for an imaginary crop-weed combination (Kurstjens 2002).

4.2.3 Fundamental research

When several types of equipments are evaluated, e.g. torsion weeder, versus finger weeder, the selectivity of the tools are relevant to evaluate, not the weed control effect itself, or the crop damage itself. Some type of intensity-response curves are useful here. In any case the tools have to be compared at similar cultivation intensity, in regards to e.g. crop damage, or else one may reach irrelevant conclusion such as one tool is more gentle towards the crop than the other, which is simply because it was used on a lower intensity also resulting in lower weed control. Weed harrowing before and after crop emergence is used in cereals and some broad-leaved crops to control weed seedlings. Weed harrows and rotary hoes have similar effects on weeds and crops in early growth stages.

Weed harrowing is normally performed with harrows with flexible spring-loaded tines. Chain harrows and other rigid tine harrows are rare in present-day experiments.

The intensity of treatment (aggressiveness) is adjusted by driving speed, angle of penetration of the tines and number of passes. Different brands of weed harrows hold different possibilities to adjust the intensity.

Weed harrows bury and uproot small weed seedlings under loose soil conditions. Weeds in late growth stages are to some extent torn. Crop injuries are often associated with weed harrowing, which limits the possibilities to obtain high degrees of weed control without associated crop damages. Selectivity is acknowledged as a key parameter in weed harrowing.

Main challenges

The main challenges in experiments with post-emergence weed harrowing is that

- there is no unambiguous method to describe the intensity of treatment
- treatments should be optimised to the combined effects on weeds and crop (low selectivity)
- plant recovery processes after harrowing make crop and weed responses time dependent
- there are no objective real-time methods to assess crop damage

Treatments

The following objectives may influence the experimental designs and approaches:

- to acquire knowledge about basic mechanism in mode of operation
- to optimise treatment at single or multiple growth stages
- to compare different implements
- to compare different methods

Mode of operation

- Guidelines are not recommended

Detailed studies of the basic mechanisms of the mode of operation should be well adapted to the given objective. Studies may be conducted in laboratories with special equipment (Kurstjens *et al.*, 2000) or in fields where simple hypotheses about the mode of operation are tested with crop plants as artificial weeds (Rasmussen, 1991). There is no sense in developing guidelines for such studies as they are highly specialized.

The optimum treatment in fields

- Use graded levels of treatments
- Adjust intensity of treatment by increasing driving speeds, number of passes and/or angle of tines
- Describe intensity of treatment in terms of attempted target response and in terms of applied equipment and adjustments
- Use weed as well as crop responses

When crop damage is associated with weed harrowing, the optimum treatment is reflected in the combined effects on crop and weeds. Both responses should be considered when treatments are planned and conducted. If possible, graded levels of experimental treatments should be carried out and crop and weed responses analysed by analysis of regression (linear or non-linear).

The intensity of treatment may be varied by increasing driving speed in the range of 2 km h^{-1} to about 12 km h^{-1}. High driving speeds require that the surface is completely plane, otherwise there will be significant treatment variation. Rasmussen (1992) used a range of driving speeds to vary intensity.

The angle of penetration of the tines is important to the intensity. Lowering the angle (high negative value according to Fig. 10) decreases the intensity of treatment and positive angles represent very aggressive treatments. Positive angles may result in unstable movements of the harrow, which should be avoided. Böhrnsen (1993) used tine angle to vary intensity.

Increasing number of passes per cultivation time increases the intensity of treatment. This is probably the most common way to increase the intensity in experiments where graded levels of intensities are used. Rasmussen (1993) used number of passes to vary intensity.

Harrowing parallel to the crop rows normally gives a more uniform treatment than harrowing across the rows. Harrowing across may, however, increase the intensity of treatment. Rydberg (1994) used direction to vary intensity.

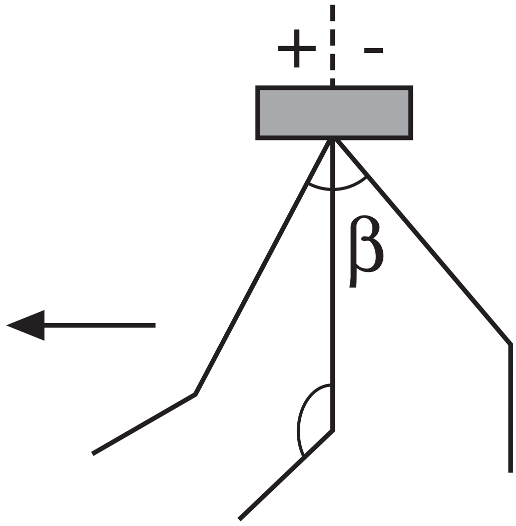

Figure 10. Shape and possible adjustments of the tines of the spring-tine harrow. The arrow indicates the driving direction. The tine adjustments range from – 45° up to + 15° where values represent the angle b between the upper part of the tine and the perpendicular to the soil surface (Peruzzi *et al.*, 1993).

4.2.4 Comparing implements

- Comparing different implements ability to control weeds without damaging the crop requires that implements are compared at the same level of weed control

Not only selectivity comparison is important. A good weed harrow is a harrow that fits to a given purpose. For example, if flexibility is a key issue, because the harrow should be applicable on different soil types and in different crops, flexibility should be the experimental main focus. If depth adjustment is a key issue, because the harrow should be applicable in small seeded crops like seeded onions and carrots, depth adjustments and depth stability should be the experimental focus. In arable crops capacity (ha h^{-1}) and homogeneity of treatment intensity are key issues.

4.3 Describing the intensity, equipment and adjustments

As outlined above, the intensity of weed harrowing treatment may be adjusted in several ways. Technical descriptions of treatments (speed, angle (Fig. 10), number of passes and direction) are often considered as an absolute necessity in the research process. However, in weed harrowing research, technical descriptions may be of secondary importance to the impacts on crop and weeds. This means that a description of attempted target responses on the crop-weed systems may provide more valuable information than a description of technical adjustments of an implement. For example, the intensity of treatment might be adjusted to create visual damages on the crop plants in the range of 5 to 50%. The description of technical adjustments only provides little information about the intensity because there exist significant and complex interactions between implement adjustments, soil and crop-weed responses. For example, a given driving speed gives totally unpredictable weed control effects in different environments.

This leads to two important points: (1) the intended intensity of treatment should be clearly expressed in terms of immediate crop-weed responses and (2) the reasoning for choosing the intensities should be outlined (for example by the procedure in 4.2.2).

If the objective of the experiment is to reveal relationships between technical adjustments and the crop-weed responses, technical descriptions are important.

As there is a wide range of different equipment for intra-row cultivation, the implement description varies from case to case. See examples of descriptions and pictures in Fig. 11, and in e.g. Ascard & Bellinder (1996) and Hallefält, Ascard & Olsson (1998).

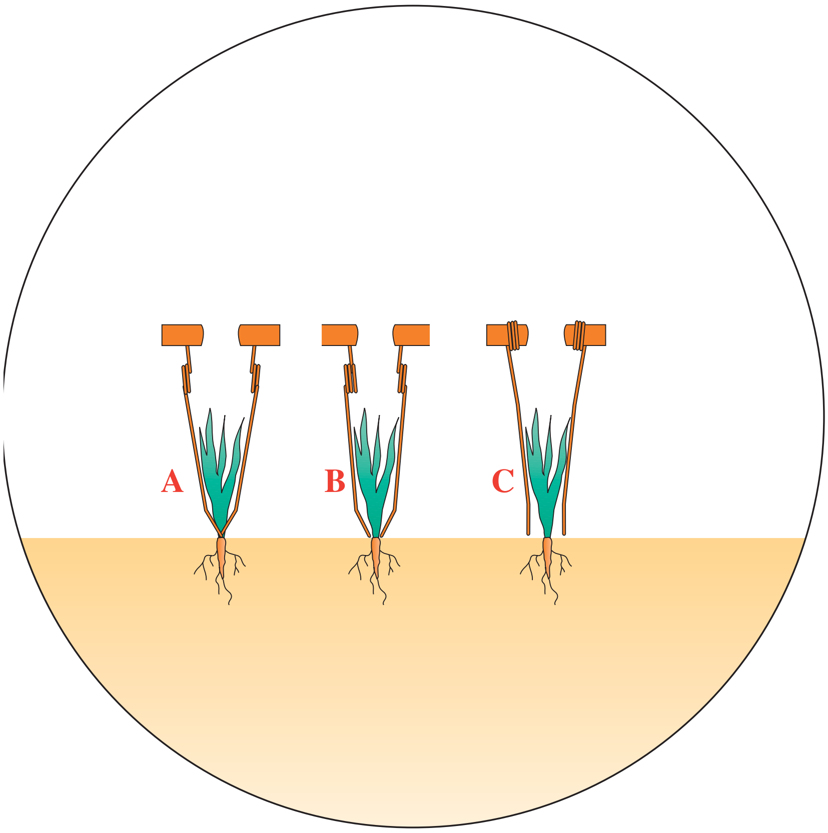

Figure 11. Possible adjustments of tools for intra-row weeding: (A) torsion weeder operated with the tines crossed; (B) torsion weeder; (C) vibrating teeth (Peruzzi *et al.*, 2003).

4.4 Assessing plant response

4.4.1 Tolerance experiments

To evaluate the general prospects of successful post-emergence weed harrowing, information on at least two crop aspects is important; the ability of the crop to resist soil covering and other damages (the initial effect and the recovery effect). Both aspects relate to selectivity. Soil covering relates to the harrowing process and tolerance relate to the plant recovery process after harrowing.

Initial crop effects may be assessed in different ways. Leblanc and Cloutier (2001a; 2001b) used density reductions and Jensen *et al.* (2004) used crop soil cover. Crop soil cover seems to be better correlated with crop yield response than density reductions in experiments with weed harrowing (Jensen *et al.*, 2004), but current disadvantages by using crop soil cover assessment in scientific work has to be overcome before this assessment is generally adopted.

If the objective is to make relative comparisons among crops or cultivars, crop yield response to harrowing in weed-free environments may give valuable information.

4.4.2 Crop soil cover

One advantage of using crop soil cover as a measure of the initial crop damage in experiments with weed harrowing is that the information is accessible at the time of harrowing and therefore may be used in real-time adjustments. Crop density is more labour-intensive to assess and it may be practically impossible to assess immediately after harrowing if crop plants are covered. However, it is less likely to be biased. This problem is particularly pronounced if different individuals assess soil cover and if absolute values are of interest.

It may, however, be possible in the near future to replace visual assessments with image analysis, which may create unbiased and reproducible assessments.

4.4.3 Determination of mechanical weed control equipment efficacy

Weed populations are generally not uniformly distributed in the field and make weed control assessment difficult and sometimes unreliable, depending on the sampling techniques used. One technique that can be used consists in using "artificial" weed populations and in determining their response to various treatments (Benoit *et al.*, 1995; Portillo-Nunez, 1996).

The method consists in using seeds of plant species that are not already present in the experimental area and in seeding them in narrow lines across the path of the equipment (generally perpendicular to the crop rows). The plants are seeded at known densities and are counted prior to a treatment and as soon as possible after the treatment and a week later. They are also counted up in the path of the cultivator in order to determine if the machinery carried some seedlings further away. Similarly, lateral displacement of seedlings can also be measured, etc. Seedling counts before and after a treatment can give a good indication of the efficacy of a cultivator. The number of seedlings buried, uprooted etc can also be determined. These cultivations have to be done when the "artificial" weed is still at an early growth stage, preferably at less than 1 leaf stage for a monocotyledonous species and less than 2 leaves stage for a dicotyledonous species.

Using crop seeds generally means that they mostly germinate at the same time, preventing confounding between the effect of the treatment and the addition of new seedlings by plants that germinated right after the treatment. Brassica seeds such as mustard were successfully used as well as seeds of ryegrass although the latter had to be treated before the initiation of tiller production (Benoit *et al*, 1995; Portillo-Nunez, 1996).

4.4.4 Determination of crop susceptibility to flex-tine harrows and to rotary hoes

A simple protocol can be used to determine crop growth stages susceptibility to various mechanical weed control equipment. In a weed-free field, all the early growth stages of the crop are cultivated systematically once (e.g. treatment 1 might be cultivated pre-emergence, treatment 2 might be cultivated at the cotyledon stage, etc). Other treatments can consist in cultivating at different combinations of crop growth stages, resulting in some plots receiving 2 or more cultivations (Leblanc and Cloutier, 2001a; 2001b). The advantage of conducting this type of experiment in a weed-free field is that there are no confounding effects with weed interference on crop yield. Herbicides can be used to insure that there are no weeds in the experimental area.

The variables that can be measured are: crop density before and after a treatment, crop damage, crop yield etc.

5 Concluding remarks

In the previous pages we have suggested some guidelines on research techniques for flame weeding, weed harrowing and intra-row cultivation, also summarized in Table 4. We are confident that this paper serves as a guideline for physical weed control research and as a basis for further discussion on and development of research methodology. We would like to emphasize that these guidelines are not intended to limit the development of new methodology, but to help exploit current methodology and improve it. The diversity of methodology is not an end itself.

However, it is evident that the topic can't be treated exhaustively within a few pages. There is still a lot to do even within the topics covered here, not to mention all the other physical weed control methods – e.g. hoeing, brush weeding, steaming, electroporation and the whole area of cultural weed control – which were not dealt with in this paper. There are also several challenges for physical weed control research methodology, which were only superficially mentioned, but would be worth a thorough discussion and should be presented in a future paper.

We feel that it would be beneficial to continue writing the guidelines. One option for that would be establishing a working group on guidelines within the Physical and Cultural Weed Control working group. The core group, working with several contributors, would prepare more thorough guidelines, which could be presented e.g. in a separate session (oral or poster) during the next Workshop, and posted on the PWC web site. Other options for continuing the work should be considered as well.

We hope that this paper acts as a catalyst stimulating thinking and discussion the subject of guidelines for physical weed control, as well as helps to raise the standard for physical weed control research.

Table 4. Checklist for research. The following checklist may be used when preparing experiments in physical weed control. All boxes should be checked before the experiment is conducted.

- ❑ The research aims are clearly defined
- ❑ An appropriate experimental design has been produced
- ❑ It is clear which statistical methods to use

We know how to describe…
  - ❑ The methodology
  - ❑ Equipment and adjustments
  - ❑ Weed and crop plants
  - ❑ Environmental conditions
- ❑ …and intend to do so
- ❑ We know when and how to do the assessments
- ❑ We know how many weed and crop plants should be counted
- ❑ We are ready to do it!

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