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THERMAL WEED CONTROL BY FLAMING:

Biological and Technical Aspects

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To Ingrid, Ellen and Martin

Abstract

Ascard, J. 1995. *Thermal Weed Control by Flaming: Biological and Technical Aspects.* Dissertation. Swedish University of Agricultural Sciences. SLU/Repro, Alnarp, Sweden.

The aim of this work was to study the influence of biological and technical factors on the effect of flame weeding, as a basis for reducing the energy consumption and increasing the effective ground speed required for good weed control. Responses of weeds and test plants were evaluated in the field. Effects of propane dose and ground speed were described by logistic models. The sigmoidal dose-response and speed-response curves imply that propane dose and the ground speed can be adjusted to the required control effect, the weed flora and the developmental stage of the plants. A 95% reduction in susceptible annual weed species, with 0-4 true leaves, was achieved at propane doses of 10-20 kg ha^{-1}, and the weeds were completely killed at 20-50 kg ha^{-1} (900-2300 MJ ha^{-1}). Considerably higher doses were needed at later stages and for more tolerant species. The most tolerant species could not be controlled with one treatment, regardless of dose. Flamers with different characteristics were studied. Flamers with covered burners were generally more effective than an open flamer, especially on larger plants and tolerant species. The effective ground speed was generally higher for flamers with a higher fuel input, but only up to a certain level. A flamer with a relatively high propane consumption of 34 kg h^{-1} per metre working width (440 kW m^{-1}) allowed an effective ground speed of 8 km h^{-1} when smaller plants were treated, whereas the effective ground speed was 2.6 km h^{-1} for a flamer with the more usual burner power of 12 kg h^{-1} m^{-1} (150 kW m^{-1}). Temperatures from the flamers were measured above the ground under weed-free conditions in the laboratory. There was generally a high correlation between different thermal parameters, e.g. the maximum temperature and the temperature sum, measured from the flamers in the laboratory, and the weed reduction in the field, although discrepancies were found. Flame weeding is useful although the method could be further improved.

Key words: dose-response, speed-response, effective dose, effective ground speed, propane, energy, temperature, flame cover, burner power, weed species

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List of papers

This thesis consists of a general discussion and the following five papers, referred to in the text by their Roman numerals:

I ASCARD J. (1994) Dose-response models for flame weeding in relation to plant size and density. *Weed Research,* **34**, 377-385.

II ASCARD J. (1995a) Effects of flame weeding on weed species at different developmental stages. *Weed Research,* **35**, (in print)

III ASCARD J. (1995b) Flame weeding: effects of burner angle. *Manuscript.*

IV ASCARD J. (1995c) Flame weeding: effects of fuel pressure and tandem burners. *Manuscript.*

V ASCARD J. (1995d) Flame weeding: effects of open and covered flamers. *Manuscript.*

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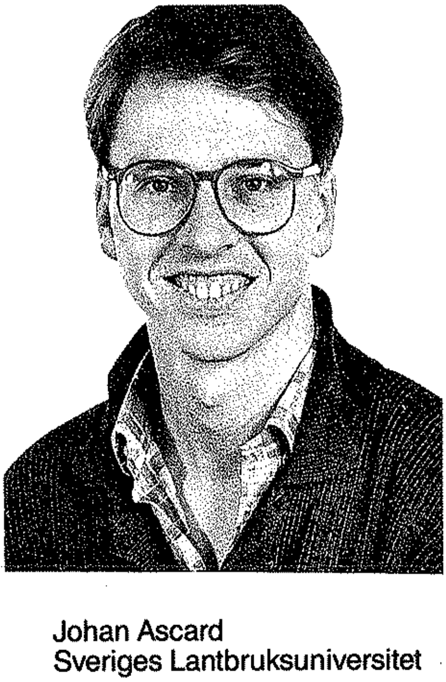
"He who is lost finds new ways"

Nils Kjær



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Content

Introduction

Flame weeding belongs to a group of thermal weed control methods, which is a collective name for different physical methods using high or low temperatures or electrical fields. A wide range of methods exists including infrared radiation (Parish, 1989a, 1989b), hot water (Berling, 1993), freezing (Fergedal, 1993) and different electrothermal methods (Wayland *et al.*, 1975; Sanwald, 1977; Diprose & Benson, 1984; Mattsson, 1993; Mätzler, 1993). It is mainly flaming, however, that is of practical use today. Flaming should not be confused with burning; flaming does not burn the plants but heats them rapidly, enough to rupture the cell membranes (Ellwanger *et al.*, 1973a, 1973b).

Flame weeding today

There is currently a renewed interest in flame weeding as an alternative to chemical herbicides. Today, flaming is widely used in Europe as an integral part of the weed control strategy in organic farming for non-selective weed control pre-emergence of the crop, in carrot and other slow-germinating row crops (Ascard, 1990; Rasmussen & Ascard, 1995). In some heat-tolerant crops, such as onions and maize, selective post-emergence flaming is also used. Other uses of flaming include weed control on hard surfaces in urban areas and desiccation of potato haulm prior to harvest (Ascard, 1988; 1989; Hoffmann, 1989; Larsson, 1992; Vester, 1987a; 1988). There is also a renewed interest for flaming in the USA and Canada (Laguë *et al.*, 1992) and other parts of the world. For example, flaming has proven to be effective in controlling the pesticide resistant potato Colorado beetle (Moyer, 1991; South, 1993).

History and development of flame weeding

The idea of flame weed control is not new. A patent on flame cultivators was obtained as early as in 1852. The large-scale agricultural application of flaming began in the early 1940s for selective weed control in cotton fields in the USA. At that time, liquid fuels such as kerosene and oils were gradually being replaced by LPG (Liquefied Petroleum Gas), mainly propane and butane (Edwards, 1964; Kepner *et al.*, 1978).

Between 1940 and the mid-1960s, flame weeding was widely used in the USA in various crops including cotton, maize, soybeans, beans, alfalfa, potatoes, onions, grapes, blueberries and strawberries (Edwards, 1964; Kepner *et al.*, 1978). By far the greatest amount of research and the most extensive application of flaming have been in selective flaming of small in-row weeds in cotton and other heat tolerant row crops. The method of using delayed sowing followed by non-selective flame weeding preemergence of the crop, was not common at this time. In fact, this method was presented as an innovation in the late 1960s by Chappell & Ellwanger (1969).

Covered flamers were developed in the 1960s in the USA for non-selective weed control between the rows of cultivated crops (Parker et al. 1965), for pest insect control in alfalfa (Luttrell & Bennett, 1968) and for potato haulm desiccation (Hansen, 1969). Other applications included thermal defoliation of cotton plants, disease control in various crops and weed control on drainage ditch banks (Edwards, 1964; Coykendall, 1968; Batchelder *et al.*, 1970; Maloy, 1970; Kepner *et al.*, 1978).

American research reports on flaming from the 1960s and early 1970s were not particularly aimed at reducing the energy consumption for flaming, probably partly because fuel was cheaper then and partly because many researchers were sponsored by the petroleum industry.

Interest in flame weeding increased during the 1950s but declined in most areas during the mid and late 1960s as a result of increasingly efficient chemical herbicides. During the 1970s, flamers disappeared from the agricultural scene as the prices for petroleum rose (Kepner et al., 1978).

In contrast to the USA, flaming was not widely used in Europe at this time. There are reports on the use of flaming for weed control in plant nurseries (Nyholm, 1950) and vineyards (Preuschen, 1968; Engel, 1969). Research was conducted by the petroleum industry in various countries including the United Kingdom, Denmark, Belgium and Sweden, on flaming pre-emergence of the crop in sugar beets, and pre- and post-emergence as well as pre-harvest flaming in potatoes (Stewart, 1965). Flaming for potato haulm desiccation was investigated and used in practice in the Netherlands (Philipsen, 1970; de Leeuw, 1972). Holmøy & Hoftun (1980) evaluated the use of flames and steam for preharvest desiccation of onion tops. Hoffmann (1989) reports additional activities in Germany and Switzerland, where organic farmers began to use flame weeding in the early 1970's.Today, flaming in Europe is mainly used for non-selective weed control in vegetables, row crops, urban areas and for potato haulm desiccation.

Effects of flaming on beneficial organisms

Flame weeding is commonly believed to cause unwanted heating of the soil and thereby have a detrimental effect on beneficial soil borne organisms. However, soil is a very good insulator and can absorb a great deal of heat energy with little increase in temperature (Reeder, 1971). Because the thermal treatment is brief, only the uppermost few millimetres of the soil are temporarily warmed up (Hoffmann, 1989, Balsari *et al.*, 1994). No significant damage to the microflora or microfauna in the soil can therefore be expected during normal flame treatment for weed control. In fact, Dierauer & Pfiffner (1993) found no species-specific effect of flame weeding on carabide beetles, in early flaming before crop emergence in vegetables. When flaming is used for pest insect control (Moyer, 1991) and disease control (Coykendall, 1968; Maloy, 1970; Bång, 1994), the target pests are exposed to the flames on the crop plants or on the soil surface. Flaming has also been tested for partial soil disinfection, where very high flaming intensities are used and the upper soil layer is lifted up and dropped through a flame curtain to expose the soil particles to the heat (Kraus, 1973; Hoffmann, 1989). This kind of partial soil sterilisation is, however, no longer used.

Costs of flame weeding

The total cost of flaming is generally greater than the cost of chemical weed control, mainly due to high machinery costs and low field capacity (Klooster, 1983; Nyström & Svensson, 1987; Ascard, 1988; Hoffmann, 1989; Larsson, 1992; Nemming, 1994). The effective ground speed, i.e. the speed required to obtain good weed control, is important for the capacity and for the total costs of flaming. Moreover, in large scale farming, high capacity is a prerequisite. For weed control in vegetables, labour costs for supplementary manual weed control make up a large part of the total cost of using flame weeding as opposed to herbicides (Ascard, 1988). Contrary to a commonly held belief, however, fuel costs are generally not the most expensive part of the total cost of flame weeding. In the crops where flaming is commonly used, the cost of propane is often similar to or lower than that of herbicides (Ascard, 1988; Hoffmann, 1989; Larsson, 1992).

Advantages and disadvantages of flame weeding

The advantages of flaming are that the flame leaves no chemical residue in the crop, soil or ground water and there is no chemical carry-over effect on subsequent crops. Propane costs are sometimes lower than herbicide costs. Flaming controls a wide range of annual weed species, some of which are tolerant or resistant towards herbicides. In some cases, the effect of flaming is less subject to variation in weather conditions than that of herbicides, especially for pre-emergence herbicides applied to the soil.

The disadvantages of flaming include the short-term effect, the low selectivity and the need for repeated application. The equipment and the labour costs for application are high compared with those for chemical application. Flaming usually has a low capacity due to narrow working widths and - for many flamers - the rather low effective ground speed. The working environment, involving gas and flames, considered by some to be uncomfortable. From a resource and environmental point of view, the high energy requirement and the release of carbon dioxide can be seen as a disadvantage, although propane combustion is relatively clean compared with other fossil fuels.

Problems to be investigated

Although flame weeding has been used for a long time, the method poses problems such as high costs, low capacity and high energy consumption. The literature on flame weeding contains few basic studies on the energy required to kill weeds. In order to lower the energy requirement, more knowledge is needed on how to adjust the treatment intensity to the weed flora and to the stage of development. More knowledge is also needed on how to improve the performance of flame weeders. In many studies, the different technical parameters are investigated. However, the effects are usually evaluated as the relative difference between individual treatments, rather than estimating the effective dose and ground speed required to obtain good weed control. Several attempts have been made to evaluate flamers based on temperature measurements, although the correlation between these measurements and the weed control is poorly understood.

Objectives

The general aim of this work was to study the influence of biological and technical factors on the effects of flame weeding in order to reduce the energy consumption and to increase the effective ground speed required to obtain good weed control. Another aim was to measure temperatures from dynamic flamers in the laboratory and to correlate these with the weed control in the field.

The first part of the work (Papers I and II) deals mainly with biological and biometrical issues, in order to develop and apply the dose-response concept, known from herbicide bioassay, to flame weeding. This concept can be used as a tool to evaluate the influence of different factors, in terms of effective propane dose required to achieve good control. More specifically, the objectives of the first two papers were:

- to describe dose-response relationships and to examine how the dose-response curve relationships were influenced by plant size and density (Paper I)

- to study the effect of flaming on weed species at different developmental stages (Paper II).

- to determine whether the total flame dose could be reduced, and the control effect increased by split applications (Paper II)

In the second part of the work (Papers III, IV and V), the general objective was to study the effect of technical factors on the efficacy of flame weeding. More specifically, the objectives were:

- to study the effect of burner angle of an open flamer on non-selective control of small weeds (Paper III)
- to study the effect of fuel pressure and tandem burners of a covered flamer on effective dose and ground speed (Paper IV)
- to study the effect of open and covered flamers, with different burner types and fuel input, on weeds and test plants, in terms of effective dose and ground speed (Paper V)
- to study the effect of flamers on temperatures under the flamers in the laboratory in dynamic conditions (Papers III, IV and V)
- to correlate the temperature measurements obtained in the laboratory with the weed control in the field (Papers III, IV and V)

The work was limited to non-selective flaming of relatively small annual weeds and test plants, using propane as the fuel, and the results are therefore mainly relevant for such applications.

Material and methods

Plant material

Naturally emerged weed mixtures were flamed in replicated experiments in the field (Papers II, III and V). The weed flora was dominated by *Capsella bursa-pastoris*, *Chamomilla suaveolens*, *Chenopodium album*, *Poa annua*, *Senecio vulgaris*, *Stellaria media* and *Urtica urens*. The main problem with the natural weed flora was the large spatial variation in weed distribution, which made any experimental work erroneous. Sown test plants of *Brassica napus* and *Sinapis alba* were therefore used in several field experiments to establish even plant stands. After the first experimental year, 1989, *B. napus* was replaced by *S. alba* as this latter species reacts more similarly to an erect annual weed species such as *C. album*. *Sinapis alba* is however generally more tolerant than *C. album* at similar developmental stage

Generally, the weeds and test plants in this study were flamed when the larger part of the population had emerged. The weeds were intentionally allowed to emerge before treatment as the purpose was to study the effect on emerged weeds rather than the effect on weed emergence after treatment. In Paper II, the time span between tillage and early treatments was 19-27 days, which corresponds to the time from drilling to emergence of slow-emerging small-seeded crops such as carrots and onions in early spring in southern Sweden. However, especially in late spring and for faster emerging crops, flaming pre-emergence of the crop has to be done before most of the weeds have emerged, which will cause a lower long-term effect than that found in this study.

At the assessments, the plants were counted and the fresh weights were recorded. The variation of the fresh weights due to variations in the moisture content of the plants was kept to a minimum by recording the fresh weights within a few hours per replicate.

Flamers

A total of six flamers with different characteristics were used, described in Paper V. The problem of ineffectual home-made flamers, obtained by covering burners designed to be used as open burners, or by uncovering burners designed to be used in covered flamers, was avoided by comparing different flaming systems designed for use either as open or covered flamers. The flamers used were chosen from commercial flamers and existing experimental flamers, to give a representative selection of different types of flamers with respect to burner type, cover, flame pattern and fuel input. Another advantage of using available flamers is that the results can be related to other studies using similar equipment. The disadvantage of evaluating different flaming systems, as in Paper V, is that any differences between flamers cannot be attributed to cover, to burner power or to burner type only, but rather to the whole flaming system. On the other hand, there is no simple way of just replacing one burner type with another on an existing covered flamer, as the whole flamer may then have to be re-designed and re-optimized in terms of burner position, cover height etc.

Due to limited resources, only a few of the flamers could be purchased for this research project. Several flamers had to be temporarily borrowed from other companies and researchers. Therefore, the flame weeders included in the experiments changed from year to year. The advantage of this is that many different flaming systems were investigated. The disadvantage is that several experiments could not be repeated. However, as the aim of this work was to study some principal issues, and to develop experimental methods, rather than give specific recommendations to users on how to use a certain machine, this lack of repetition was considered acceptable.

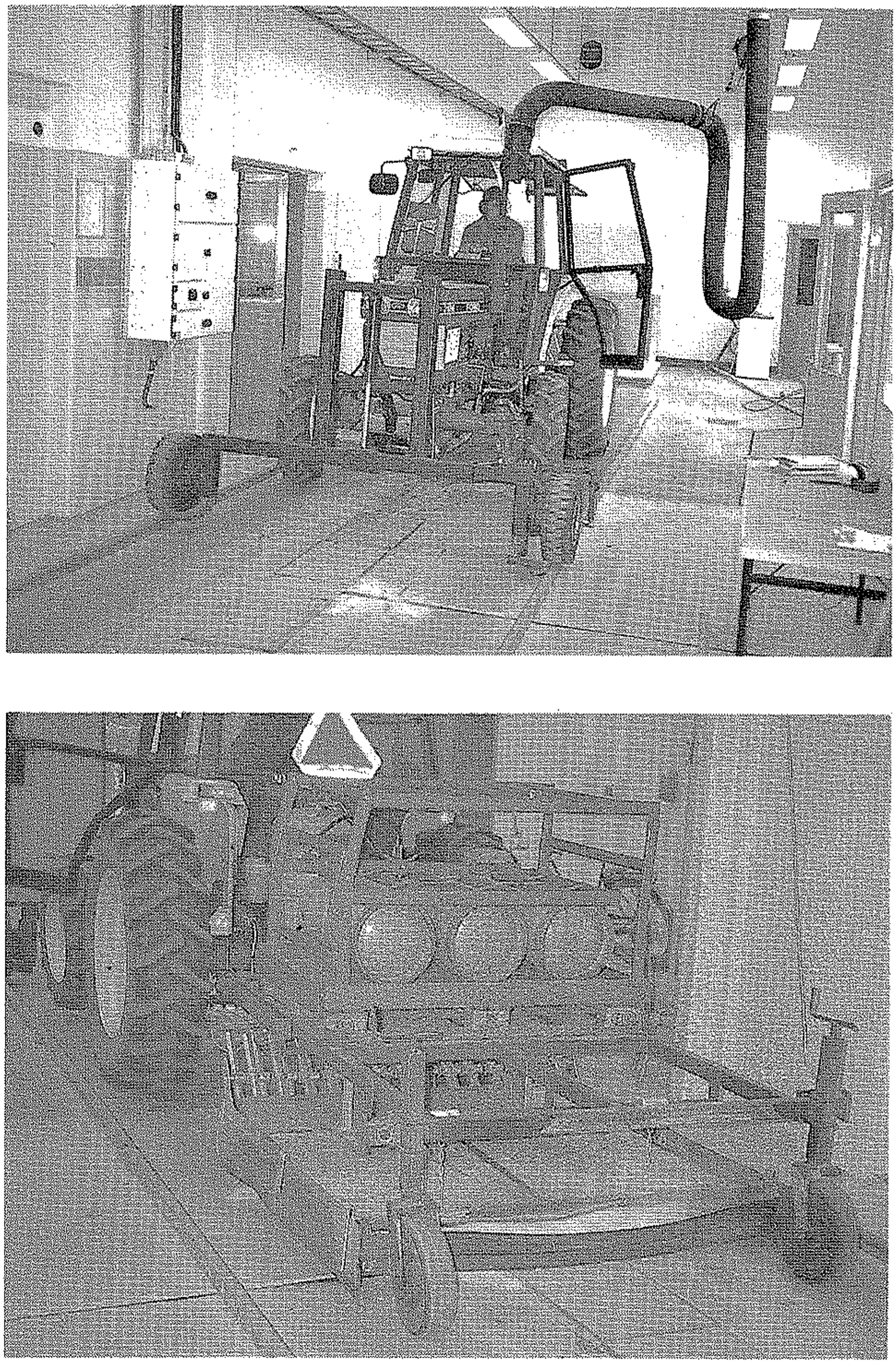

Fig. 1. Tractor-mounted flamer in the laboratory railtrack used for temperature measurements. Front view (top), rear view (bottom).

The propane consumption was determined in repeated tests by weighing the propane tanks before and after each test. The propane consumption of all burners on a flamer unit, rather than single burners, was measured. To make the figures comparable, they were converted to propane consumption per hour and metre working width.

Weed control experiments in the field

Most field experiments were designed as dose-response experiments. The exceptions were the split application experiments (Paper II) and the field evaluation of burner angle (Paper III), that were designed as ordinary randomized block experiments.

In all dose-response experiments, the propane dose per unit area was varied with the ground speed. The appropriate range of ground speeds were based on preliminary experiments and previous experience. The aim was to obtain plant responses from 0 to 100%, evenly distributed on a log dose scale. In the early experiments, from 1989 to 1991, the range of ground speeds was determined individually for each experiment. In later experiments, in 1992 and 1993, the ground speeds were chosen from a fixed number of ground speeds (0.5, 1, 2, 4, 6, 8 and 12 km h^{-1}) in order to facilitate the experimental procedures. The ground speeds were determined by repeated measurements of the time taken by the tractor to travel a certain distance.

Dose regulation by adjusting the ground speed is considered a suitable method in flaming bioassay. There is, however, no method for adjusting the propane dose, which does not also alter the overall performance of the flamer. A flamer with a high burner power may have a sub-optimal combustion at low ground speeds (Paper IV and V). By changing the gas pressure, the dose can only be regulated within a limited interval. Vester (1990) and Rahkonen & Vanhala (1993) used a combination of fuel pressure and ground speed to obtain a wide dose range. One objection to altering the fuel pressure is that this also changes the propane combustion, the flame length and the resulting penetration of the flame. As a result, the energy efficiency of the flamer may vary when the fuel pressure varies (Vester, 1990; Paper IV).

Temperature measurements in the laboratory

Temperatures were measured above the ground in a rail track in the laboratory, with the same flamers and adjustments that were used in the field experiments, as described in Paper III and IV. In the laboratory, however, a series of ground speeds (0.5, 1, 2, 4, 8 and 12 km h^{-1}) was used, similar for all flamer settings. The flamers were carried by a tractor, equipped with an extractor fan for the diesel exhausts, guided along a 25 m long rail track (Fig. 1). The temperatures were measured 1 cm above ground in replicated experiments, by thermocouples of type K (Chromel-Alumel). In some experiments, temperatures were also measured at a height of 3.5 cm (Paper V). In the early measurements, the temperatures were recorded by two types of thermocouples, with a wire diameter of either 0.25 mm or 0.13 mm (Papers IV and V). However, the thinner thermocouples were very fragile and broke easily, especially when the stronger flamers were used at low ground speeds. In addition, the thermal parameters obtained from the 0.13 mm thermocouples did not give higher correlation with the weed control than those from the thicker ones. Therefore, only the 0.25 mm thermocouples were used in the later measurements.

Statistical methods

Weed control data obtained in the field

Most of the field experiments were designed as dose-response experiments and were analysed with regression. The split application experiments (Paper II) and the field experiment on evaluation of burner angle (Paper III) were subject to standard analysis of variance.

The design of the dose-response experiments was inspired by the bioassay concept by Finney (1971, 1979). The results were analysed by non-linear regression methods similar to those developed for herbicides (Streibig, 1988; Streibig *et al.*, 1993a). The response of the plants to varying ground speeds is a new concept, developed in this work (Papers IV and V). The speed-response models were obtained by re-expressions of the dose-response models. The methods and models are further described in the section "Quantitative assessment" in this thesis, and in Papers I, II and IV.

Temperature data obtained in the laboratory

From each replicate, one average temperature-time curve was calculated, which was analysed for the maximum temperature, the "exposure time" above a certain base temperature, and the temperature sum, based on the area between the time-temperature curve and a base temperature (Papers III, IV and V). For the 0.25 mm thermocouples, the base temperatures 100°C and 400°C were used, as they correspond to flame treatments that gave roughly zero reduction of the fresh weights (100°C) and plant number (400°C) of the test plants in the field experiments. The temperature measurement were evaluated with standard analysis of variance.

The maximum temperature, the time above a certain temperature and the temperature sum correspond to those used by Harris *et al.* (1966, 1968) and Buttiglieri *et al.* (1967), although they used other names for the thermal parameter and a base temperature of 93°C for the temperature sum. For the exposure time, Harris *et al.* (1966, 1968) used several base temperatures between 93 and 982°C. The temperature sum is also related to the "utilization factor", i.e. temperature sum per unit propane, used by Storeheier (1994).

Correlation between temperature and weed control

Non-linear regression analyses were also used to evaluate the correlation between the different thermal parameters measured in the laboratory and the weed reductions obtained in the field experiments (Papers IV and V). For each temperature recording obtained at a certain ground speed in the laboratory, the corresponding weed reduction was calculated according to the estimated speed-response model. However, weed reductions were only calculated in the speed range corresponding to the ground speeds used in the field.

Several s-shaped models were tested, and three models were empirically found to reasonably well describe the relation between the different thermal parameters and the weed control. The same type of logistic model that was used for dose-response relationships was also used as a base model for describing the relation between the temperature sum and the weed control, as the temperature sum was often approximately linearly related to the dose. The methods are further described in Paper IV.

Heat required to kill plants

The effects of flaming are influenced by several factors including temperature, exposure time and energy input. The flame treatment blanches, rather than burns the plants. The effect of flaming on plants depends both on a direct effect on the cell membranes and on an indirect effect during the subsequent desiccation of the tissue. Generally, direct heat injury involves denaturation and aggregation of membrane proteins causing an increase in cell permeability and death (Sutcliffe, 1977; Levitt, 1980). Depending on the exposure time, the denaturation of cells may start already at temperatures of 45°C (Sutcliffe, 1977; Levitt, 1980; Bertram, 1994). Cellular death after flame treatment is, according to Ellwanger *et al.* (1973a, 1973b), primarily due to the initial thermal disruption of cellular membranes rapidly followed by dehydration of the affected tissue.

Lethal temperatures in leaves and stems are commonly reported in the range from 55 to 94°C (Anderson *et al.*, 1967; Daniell *et al.*, 1969; Hansen *et al.*, 1970; Porterfield *et al.*, 1971; Hoffmann, 1989). Exposure times to the flame in the range from 0.065 to 0.13 s are reported to be enough to kill leaf tissue and weeds (Thomas, 1964; Daniell *et al.*, 1969).

Several studies indicate that higher temperatures are more effective than lower for causing plant damage. Daniell *et al.* (1969) found that the structural changes within the cells were more pronounced when the temperature of the cell changes rapidly, as in a flame treatment, than when the temperature changes were more gradual, as in a hot-water-bath treatment. In general, lethal temperature varies inversely with exposure time, and a negative exponential relationship between lethal temperature and lethal exposure time is reported (Sutcliffe, 1977; Levitt, 1980). Other curvilinear relationships have also been found (Batchelder *et al.*, 1970; Lalor & Buchele, 1970; Bashford *et al.*, 1972), but they all have in common that a considerably lower exposure time is needed as the temperature increases. Based on this relationship, it can be shown that the lethal temperature sum will also be lower as the temperature increases, which was verified by Storeheier (1991, 1994). This can be explained by the higher heat transfer rate to the plants at higher temperatures (e.g. Bertram, 1994). Contrary to the findings mentioned above, Hoffmann (1990) argues that a certain amount of heat must act on the leaf surface, and that it does not matter whether this amount of heat is achieved by a high temperature during a relatively short time or by a lower temperature during a longer time. However, no data or references are given to support this statement.

Although the temperature measured in a stationary flame is essentially unaffected by fuel input (e.g. Buttiglieri *et al.*, 1967), in dynamic conditions, more heat will be transferred from the flame to the point of measurement at a given time as the energy input increases. In fact, higher temperatures and weed control were obtained from flamers with high burner power than from those with lower fuel input at similar ground speeds (Papers IV and V). This is explained by the fact that as the fuel pressure or nozzle size of a burner is increased, the gas velocity and the energy density of the flame and thereby the forced convection to the plants also increase .

On the other hand, the heat losses may be greater at higher temperatures and energy inputs. Therefore, the energy efficiency may be both higher and lower for a flame weeder with a high energy input, depending on the design of the flamer. This was evident in Paper V (Expts. 2 and 3), where the covered flamers with high burner power (440 and 540 kW m^{-1}) generally showed either similar, lower or higher energy-efficiency than other covered flamers with lower burner power (90 to 150 kW m^{-1}), depending on the treatment conditions. The lethal exposure time was also reduced to a certain extent, measured as an increased effective ground speed, by using the more powerful flamers.

Quantitative assessment

Qualitative versus quantitative assessment

In flame weeding research, the flame treatments are usually compared at a few pre-set intensity levels, often quantified by e.g. the ground 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. However, it is often more useful to do a quantitative assessment to determine the effective dose or ground speed required to obtain good control. This result will also be more relevant to the applicator.

An example of the disadvantage of evaluating the effect at a single dose level can be seen in Paper III. At that particular propane dose (49 kg ha^{-1}), the reduction of *Senecio vulgaris* was not significant compared with the untreated control. Similar observations have been made by Swedish growers, who based on their observations have concluded that *S. vulgaris* cannot be controlled by flaming. However, when a series of doses was applied and a dose-response curve was established, it was clearly shown that *S. vulgaris* could be controlled effectively at higher doses (Paper II).

Another example of the problem associated with evaluating the effects at a single dose or ground speed is comparisons of flaming techniques. If the effect of two flamers with different burner power is evaluated at the same ground speed, an analysis of variance will probably show that the flamer with the higher burner power gives a better weed control than the flamer with a lower burner power. Such results are not uncommon in flame weeding research. However, they are not useful for determining the energy-efficiency of the implements. If instead, the same flamers are evaluated at the same dose level, a relevant comparison of the weed control effect can be made, but this comparison will not be useful for determining the effective dose either. Moreover, the dose level chosen for such vertical assessment will greatly affect the size of any difference.

By using a series of doses and establishing dose-response curves, equipotent treatments can be compared by horizontal assessment, and effective doses and ground speeds can be estimated. Moreover, patterns in the mode of action, that will otherwise be difficult to reveal can be studied. The use of dose-response curves has recently become quite popular in herbicide research, especially in Denmark (e.g. Streibig *et al.*, 1993a, 1993b). Dose-response curves have also been used for natural compounds for weed control (Ascard & Jonasson, 1991; Hansson, 1994). A related concept with intensity-response curves for mechanical weed control has been developed by Rasmussen (1991). However, in flame weeding research, this bioassay concept has not yet been widely adopted, although dose-response relationships are discussed in some reports (Castille & Ghesquière, 1985; Rahkonen & Vanhala, 1993; Vester 1987b; 1988). The first real attempt to establish dose-response curves for flaming was made by Vester (1990), who over a limited dose range fitted a straight line between the logarithm of the plant response and the propane dose per unit area.

Dose-response models

This study shows that the logistic model used in herbicide bioassay (Streibig *et al.*, 1993a) or modifications of this, can generally be used to describe plant responses to flaming at different doses (Papers I, II, IV, V). In general, the logistic models (1) and (2) gave good descriptions of the dose-response relationships.

$$y = \frac{100 - C}{1 + (x/a)^b} + C \tag{1}$$

In Model (1), y is the response in per cent and x is the propane dose per unit area. The model has an upper limit of 100, a lower limit C, and is symmetric around its point of inflexion, a, on a log dose scale (Fig. 1). Parameter b describes the slope of the curve around a. Parameter a is the effective dose that gives a response half-way between the upper and lower limit.

When the plants were completely killed at high doses, Model (2) was used with a lower asymptote equal to zero:

$$y = \frac{100}{1 + (x/a)^b} = \frac{100}{1 + \exp(b(\log x - \log a))} \tag{2}$$

The re-expression to the right in model (2) makes it easier to see the similarities with other commonly used logistic models (Streibig, 1988, Ratkowsky, 1990) and

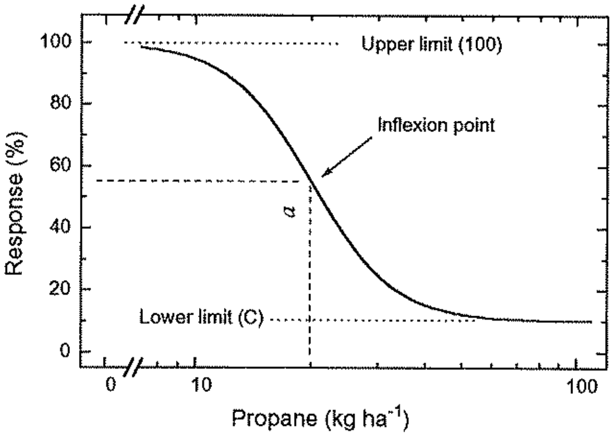

Fig. 2. Dose-response curve according to Model (1): a=20, b=4, C=10 .

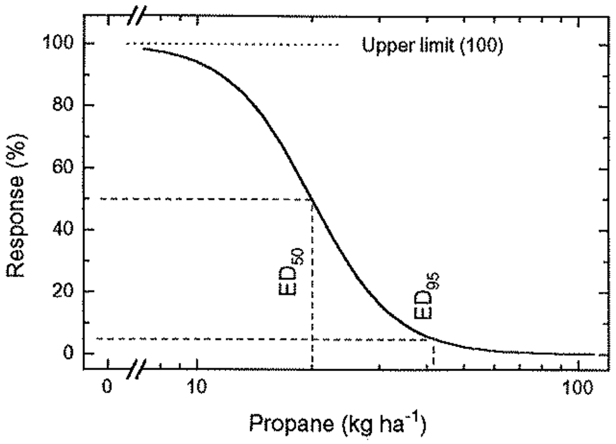

Fig. 3. Dose-response curve according to Model (2) and (3): $a(=ED_{50})=20$, $ED_{95}=41.8$, $b=4$.

to intuitively understand why the models are symmetric on log dose. In Model (2), parameter a is the effective dose that gives 50% reduction (ED$_{50}$). By re-parameterizing (2), the effective dose required to achieve a reduction of 95% (ED_{95}) was expressed as a parameter in the model (Fig 3):

$$y = \frac{100}{1 + (x/ED_{95})^{b} 19} \qquad (3)$$

which is further described in Papers II and IV. The logistic dose-response models were modified to describe deviations from the symmetry (Paper I), and to describe increased emergence and growth at high flame doses (Paper II).

If the dose-response curves are parallel, the horizontal distance between the curves is the same on a log dose scale, which means that there is a certain per cent difference in dose requirement regardless of response level. However, as the dose-response curves in many cases were not parallel, the response curves were generally evaluated at a certain control level.

Depending on the control situation, different response variables and control levels can be chosen. In grain crops, 80% control effect on weed weight may be sufficient, but in most situations where flaming is used, for example, in flaming pre-emergence of the crop, it is desirable to kill as many weeds as possible, since surviving weeds need further control. In this thesis, the doses needed for 95% control were estimated, in addition to those giving 50% control. Even higher control levels are interesting, but the calculations of LD_{99}, which were estimated in a progress report (Ascard, 1992a), are more uncertain, especially if these estimates are beyond the observed dose range.

Speed-response models

The same type of logistic model used for describing dose-responses, was also used for speed-responses. To describe the response of different ground speeds, the dose (x) in (1) and (2) was replaced by:

$$x = \frac{10p}{v} \tag{4}$$

where p is a constant describing the burner power for a particular flamer set-up, expressed as the propane consumption in kg h^{-1} m^{-1}, v is the ground speed in km h^{-1}, and 10 is a constant used to obtain the dose in the unit kg ha^{-1} (instead of kg per 1000 m^2). By replacing x in (2) with the expression in (4), v became a parameter in the following model:

$$y = \frac{100}{1 + (10p/av)^b} \tag{5}$$

Model (5) was simplified by replacing $10p/a$ with α:

$$y = \frac{100}{1 + (\alpha/v)^b} \tag{6}$$

where parameter b is the same as in (2). Parameter α is the inflexion point of the speed-response curve, which in Model (6) is equal to ES_{50} (Effective Speed) (Fig. 4). By re-parameterizing (6), the effective speed required to achieve a reduction of 95% (ES_{95}) was expressed as a parameter in the model:

$$y = \frac{100}{1 + (ES_{95}/v)^b 19} \tag{7}$$

which is further described in Paper IV.

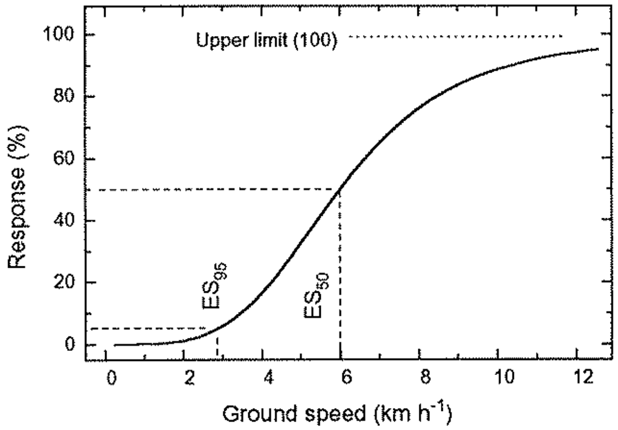

Fig. 4. Speed-response curve according to Model (6) and (7): $\alpha(=ES_{50})=6$, $ES_{95}=2.9$, $b=4$.

Significance of the slope of the dose-response curve

In herbicide bioassay, compounds with the same mode of action are assumed to have the same slope and thus have parallel dose-response curves (Streibig, 1988). It may be tempting to apply the parallel-line assay to flame weeding, but there are several reasons for non-parallel curves, even though the "mode of action" may appear to be similar.

Generally, the slope of the dose-response curve supplies information about the variation in control effect within the plant stand. A slight slope, i.e. a low value of parameter *b* in (1), (2) and (3), indicates an uneven reaction of the plant population to the treatment. Such variation can be due to both biological and technical factors.

A large variation in control effect may be due to genetic differences in heat tolerance within and between species in the plant population. It may also be due to differences in size between individual plants. Since the flame treatments in this study were often conducted in different plant stands and at different treatment times within the same experiment, differences in the prevailing treatment conditions caused different slopes of the response curves in many experiments (Papers I, II, IV and V).

There is a principal difference between the dose-response curves for plant number and fresh weight, as Vester (1990) also pointed out. Even a low, sublethal dose will result in a reduction in fresh weight, whereas a certain dose is needed to reach the sensitive parts and thereby kill a plant completely. Therefore, the dose-response curves describing the effects on plant number are displaced to the right. When even plant stands of *Sinapis alba* were flame treated, the slopes of the curves describing the effect on plant number were steeper than those for fresh weight (Papers I, IV and V). However, the slopes of the dose-response curves for natural weed mixtures show inconsistent results (Papers II and V), which may be due to uneven weed stands.

A slight slope may also be attributed to variations in the control effect, due to uneven soil conditions, or irregular performance of the flame weeder. An uneven application technique of flaming will probably influence the shape of the dose-response curves in the same manner as in herbicide application (Alness & Hagenwall, 1994). However, a flat slope is not necessarily a sign of poor overall performance of the flame weeder. The covered flamers gave flatter slopes of the dose-response curves than those for the open flamer (Paper V). This may be a result of the covered flamers being able to reduce the plants to a certain extent also at very low doses.

Effects on weeds

Flame weeding is effective mainly on small annual weed species, as a normal flame treatment only affects the plant parts above the soil. Plant species with growing points below the soil surface will, therefore, survive and regrow after flaming. Because of this superficial effect it is, however, possible to flame, for example, carrots just before crop emergence without damage to the crop.

Complete desiccation of plant parts above the ground is possible with most weed species as long as the flame dose is sufficiently high, although the necessary dose may vary considerably depending on weed species, developmental stage, flaming technique and environmental conditions. The most important factor distinguishing sensitive and tolerant species is not the heat tolerance of the leaves, but rather the ability of plants to regrow after the flame treatment, which is decisive for obtaining a sufficient duration of effect (Paper II).

Sensitive and tolerant groups of weeds

Weed species can be divided into four groups according to their tolerance to flaming (Paper II). Sensitive species have a taller stature with growth points located at the shoot apex and along the stem, where the flames can easily reach them. Tolerant species, on the other hand, have a prostrate growth habit with protected growth points often near the soil surface. The regrowth was rather quick in many tolerant species, even when the leaves were completely desiccated, although this regrowth required adequate soil moisture.

The first group consists of sensitive species with unprotected growth points and thin leaves, such as *Chenopodium album, Fumaria officinalis, Urtica urens* and *Stellaria media.* These species could be completely killed by a single flaming at relatively low doses. At early stages, when the plants had 0-4 true leaves, a 95% reduction of the plant number was achieved at 10-20 kg ha^{-1} and they were completely killed at doses of 20-50 kg ha^{-1}, depending on species and treatment conditions. At later stages (4-12 leaves), considerably higher rates (50-200 kg ha^{-1}) were needed to kill the plants completely.

The second group contains moderately sensitive species that could also be completely killed with a single flame treatment, both at early and late developmental stages, but which required higher doses than the species in the first group. This group contains species such as *Polygonum persicaria* and *Senecio vulgaris,* with an upright growth habit and/or quite heat-tolerant leaves and species with a prostrate habit and protected growth points such as *Polygonum aviculare. S. vulgaris* with 1-2 true leaves were completely killed at doses above 30 kg ha^{-1}, but at later stages considerably higher rates (up to 200 kg ha^{-1}) were needed to kill all plants.

The third group contains flame-tolerant species such as *Capsella bursa-pastoris* and *Chamomilla suaveolens* that could be killed completely by a single treatment only at early stages with less than four true leaves. These species have a prostrate habit at early stages and, especially at later stages, protected growth points. When these species had 2-4 true leaves, *C. bursa-pastoris* needed 35-50 kg ha^{-1} to be completely killed, whereas *C. suaveolens* needed more than 100 kg ha^{-1}. At later stages, these species could not be controlled with one treatment, whatever the dose, because of their regrowth capacity.

The fourth group contains very tolerant species with a creeping habit and protected growth points that could not be completely killed by one treatment, regardless of dose or developmental stage. In this study, the only grass species was *Poa annua*, but other grass species also belong to this group (Ensign, 1973; Dierauer & Stöppler-Zimmer, 1993; Rahkonen & Vanhala, 1993). Even when the leaves were completely desiccated, regrowth took place from growth points at or below the soil surface.

The relative tolerance of weed species in this study corresponds with previous reports (Vester, 1987b; Ascard, 1989; Dierauer & Stöppler-Zimmer, 1993; Netland *et al.*, 1994). Furthermore, the proposed grouping of weed species with regard to their tolerance of flaming largely agrees with Vester (1985; 1987a; 1990). However, in the present study, the tolerant species can be divided into groups that can or cannot be killed by one flaming at early stages.

Stimulation of emergence and growth by intensive flaming

At high flame doses, increased emergence and growth of *Poa annua* and *Capsella bursa-pastoris* was observed (Paper II). *Chamomilla suaveolens* was very tolerant and also showed a tendency towards increased growth at high doses in some experiments. This increased emergence of *C. bursa-pastoris* and the high tolerance of *C. suaveolens* agree with the results of Fykse (1985b), who showed that the germination of seeds in these species was either increased or not significantly influenced by flaming. He also showed a poor effect on *C. suaveolens*, due to regrowth of treated plants and new germination after flaming. Fenwick & Lien (1968) also showed that flaming may either increase or decrease germination of different species, and suggested that flaming may have increased germination by breaking the dormancy of seeds on the soil surface. However, since plots treated with high flame doses became relatively weed-free, increased germination might alternatively be attributed to increased sunlight and nitrate concentration in the bare soil (Roberts & Benjamin, 1979; Pons, 1989).

Single and split application

Split applications may improve weed control, as with herbicides (e.g. Jensen, 1992), since they make it possible to target a larger proportion of weeds at the sensitive cotyledon stage than is targeted with a single full-dose application. However, split application with two half-dose treatments one week apart did not give a higher plant number reduction than a single late flame treatment at the same total dose, when naturally emerged weeds were flamed at early stages (Paper II). One reason why split applications were not more effective than a single full-dose application, is that the weed flora consisted predominantly of susceptible weed species, *Chenopodium album* and *Fumaria officinalis,* which could be easily controlled by a single later application. Moreover, the larger part of the weeds were emerged at the time of treatment, and therefore, there were few additional newly-emerged weeds to be controlled by the second treatment.

This result agrees with that of Parish (1990b), who found that a late flame treatment was more effective than an early one. He obtained the highest weed reduction with a combination of early and late full-dose treatments, but two half-dose treatments were not tried.

The long-term effect of flaming depends largely on the extent of weed emergence after treatment (Parish, 1990b; Ascard, 1992b). Therefore, flaming before crop emergence is usually dose as late as possible in order to target as many weeds as possible, although not all will be at their most susceptible stage. A split application cannot be generally recommended for flaming preemergence of the crop, but may be useful when the germination period is long, in order to target the weed seedlings of tolerant species before they grow out of the sensitive cotyledon stage. Split applications may also be useful in selective flaming in order to reduce crop damage. In some cases, even repeated flaming during the same day may be justified (Lien *et al.*, 1967).

However, split application or rather repeated applications of normal doses are necessary to starve larger plants and heat tolerant weeds such as grasses and perennial weeds, that will regrow after a single treatment. When *Sinapis alba* plants at the six-leaf stage were treated, the fresh weight reduction was higher after two half-dose applications 3 or 13 days apart than after a single early full-dose treatment (Paper II). In order to starve the plants sufficiently, the second flaming should be done after an initial regrowth but before regrowing shoots have become too tolerant (Vester & Rasmussen, 1988; Roth-Kleyer & Russ, 1993).

Influence of biological factors

The tolerance of different plant parts of flaming depends on several biological factors such as protective layers of hair and wax, lignification, and conditions of water status. However, plant survival of high flame doses is largely dependent on the plant's ability to regrow after flaming (Vester, 1990, Paper II).

Heat sensitive plant parts

Young seedlings are often very sensitive to high temperatures; the region of the stem or hypocotyl close to the soil surface is often the most susceptible (Sutcliffe, 1977). For example, the thin and delicate hypocotyl of *Chenopodium album* and *Sinapis alba* is very heat sensitive at the cotyledon stage and once damaged, the plant cannot regrow (Vester, 1990, Papers I and II). Another critical part of the young plant is the shoot apex. However, in some species, the location of these sensitive plant parts is different during different developmental stages. In older plants, the shoot apex is often protected by surrounding leaves. Moreover, the larger amount of reserve food in the roots increases the plant's ability to regrow. To prevent regrowth from old plants, the flame must penetrate the leaf canopy and also reach the axillary buds at the lower nodes, which may be protected by surrounding leaves, leaf sheets and petioles. When flamed at moderate doses, the plant parts above the ground will only partly desiccate and the sensitive parts may be only partly damaged. The ability of the damaged plants to regrow will then depend on the energy reserves of the plants, environmental conditions such as soil moisture, and competition from neighbouring plants.

Stage of development

Young dicotyledonous plants are generally more susceptible than older plants to flaming. However, Lalor & Buchele (1970) showed the opposite for soybeans at the cotyledon stage. The higher thermal sensitivity of younger plants is generally caused by their thinner leaves and stems and less protected meristems than on older plants.

In general, the developmental stage has a major influence on the effective dose requirement (Papers I, II, IV and V). Propane doses of 10-40 kg ha^{-1} (500-1800 MJ ha^{-1}) were required to achieve 95% control of plant number for sensitive weed species with 0-4 true leaves, whereas plants with 4-12 leaves required 40-150 kg ha^{-1} (1800-6900 MJ ha^{-1}), depending on species, developmental stage and treatment conditions (Paper II).

Plant size

The size of the plant is related to the developmental stage mentioned above. An additional explanation for the higher dose requirement to kill larger plants is the greater leaf- and stem-surface and greater biomass to heat. As the stem- and leaf-length increases, the heat transfer coefficient will decrease (Bertram, 1994).

The relationships between the lethal dose requirement and different variables describing the plant stands at treatment time were analysed with multiple regression (Paper I). There was a significant linear relation between fresh weight per plant and the effective dose for a plant number reduction of 95% (LD_{95}) (Paper I). The fresh weight per unit area also showed a significant influence on the effective dose required for high fresh weight reduction. Although this kind of comparison has to be done with great caution, it is a possible method to compare lethal doses between assays in future studies.

Plant density

Plant density has only a minor influence on the dose required to achieve a certain percentage control (Paper I). Thus, as long as plant size remains the same and the growing points of the plants are not covered by neighbouring plants, the dose required to achieve a certain percentage control does not seem to be affected by varying plant densities. However, if the aim of the treatment is to get below a certain threshold in absolute numbers, the effective dose will of course be affected by the weed density. For example, to reach a control level of 2 surviving plants per m^2, the effective propane dose was 60 kg ha^{-1} at a plant density of 195 plants m^{-2} and had to be raised by 17% when the plant density was twice as high (Paper I).

Influence of environmental factors

Generally, plants may survive flaming by either avoidance or heat tolerance. Weeds can avoid the heat by being protected by water on the leaf surface or by being hidden by soil crumbs.

Moisture

Leaf surface moisture will prevent heat from a flame treatment penetrating different plant parts. Thermodynamic modelling by Bertram (1991) showed an almost linear decrease in heat transfer to the plants with increasing leaf moisture in the range from 0 to 50 g m^{-2}. Parish (1990a) found reduced effect of the flame treatment with increased level of water applied to the leaves in the range from 90 to 360 g m^{-2}.

Considerably higher doses were required in the dry year of 1992, than in the two previous years with moist weather (Paper I). The high dose requirement in the dry year may seem to be contrary to the common belief that the effect of flaming is most effective in dry weather conditions (Batchelder & Porterfield, 1965; Batchelder *et al.*, 1973; Hoffmann, 1989; Vester, 1988). However, in all experiments in Paper I, the flame treatments were conducted on dry plants. The reason for the high dose requirement in 1992 may, therefore, be some physiological difference, such as a more dense covering of hair and wax on the plant surface and a lower moisture content in the plants due to the dry weather.

Soil surface

The smoothness of the soil surface affects the performance of flame weeding. In selective flaming, a rough surface and soil ridges will cause flame deflection upwards, which is detrimental to the crop (Parker *et al.*, 1965; Matthews and Tupper, 1964; Perumpral et al.; 1966). The surface conditions are also important in non-selective flame weeding to avoid flame deflection upwards and to achieve an effective heat treatment close to the soil surface. Small weeds can otherwise be shielded from the flame by soil crumbs on rough surfaces. In Paper III, considerably lower temperatures were measured 1 cm above the soil surface between the ridges on a rough surface than on a smooth surface. Uneven weed control has also been observed on rough surfaces in the field (e.g. Ascard, 1992b).

Wind

Wind disturbs the performance of the flame, especially on open flamers without cover (Klooster, 1983; Vester, 1985; Geier, 1987). The open flamer used in this study was no exception (Papers III and V). Covered flamers can also be sensitive to wind, especially to wind penetrating under the flame cover from behind (Luttrell & Bennett, 1968).

Inflammable material

The presence of inflammable dry materials that can be set alight during flaming is a factor indirectly related to the effect of flaming. When flaming is used in orchards and ornamental shrubberies, crop leaves are easily damaged by the after-burning caused by fires starting in the dead weeds and rubbish (Ascard, 1988). This problem, encountered with flaming in several perennial crops, can be solved by mounting a sprayer to apply water immediately after flaming (Hansen, 1964). The risk of fire will also be eliminated if hot water is used as a heat carrier (Berling, 1993).

Influence of technical factors

Heat transfer system

Several heat transfer systems can be used for thermal weed control, as described in the introduction. Two fundamentally different types of thermal weeders are currently available on the market, both using LPG (propane/butane mixture) as fuel. Flaming is the most common. Propane flames generate flame temperatures of up to 1900°C (Lewis & von Elbe, 1987), although considerably lower temperatures are measured by thermocouples. Several types of flamers exist, some with open burners and others with burners underneath an insulated cover. The other type uses an infrared (IR) radiant gas burner, that operates at red brightness temperatures of about 900°C with essentially no visible flame on the combustion surface. These burners heat ceramic and or metal surfaces which then radiate heat towards the target. This kind of IR radiator was tested for thermal defoliation of cotton in the USA during the 1960s (e.g. Reifschneider & Nunn, 1965). IR radiators were introduced for thermal weed control in Europe in the mid 1980s by a Dutch company, Agro Dynamic/Hoaf (Van't Rood, 1985). These pure infrared radiators have not, however, become commonly used. Several investigations and practical experience indicate that pure infrared radiation is inferior to flaming in terms of weed control, energy efficiency, capacity and costs (e.g. Castille & Ghesquière, 1985; Geier, 1987; Klooster, 1983, Nyström & Svensson, 1987; Hege, 1989; Parish, 1989a). However, a closer look at these reports reveals a more complex picture. For example, the performance of IR and flame weeders seems to interact with the plant species. Parish (1989a) achieved similar control of *Sinapis alba* with electrical infrared emitters and propane flamers at similar energy inputs, but the energy requirement to control ryegrass (*Lolium italicum*) was considerably higher for IR radiation than for the flamer. My own investigations (Ascard, unpublished) agree with those of Parish (1989a).

Unfortunately, there is a great deal of confusion in the literature regarding the term "infrared" within thermal weed control, as the Dutch company that introduced the IR radiator for weed control in Europe is now marketing mainly thermal weeders with covered flame burners, but continues to market them as "infrared" weeders. The effect of this and other types of covered flamers is achieved both directly by the flames and to some extent indirectly by infrared radiation from the insulated cover, heated by the flames. A covered flamer of this so-called "infrared" type was investigated in Paper V (Flamer No. 2), and was found to have an overall performance similar to that of other covered flamers. However, the pure infrared radiators and covered flamers have different performance (Nyström & Svensson, 1987) and should not be lumped together as done by e.g. Hoffmann (1989).

Burner type

Several burner types have been used for flaming (Edwards, 1964, Parker *et al.*, 1965; Kepner *et al.*, 1978, Vester, 1987b, 1988; Ascard, 1988; Hoffmann, 1989). Burners are commonly grouped according to the shape of the burner and the flame (flat or tubular) and according to whether they have a vapour chamber or not (liquid- or gas-phase burner). There are no consistent results on which kind of burner is the most appropriate for weed control. Results by Holmøy & Storeheier (1995) indicate that flat burners producing a broad, thin and short flame are preferable for selective flaming with open inclined burners, whereas tubular burners producing long narrow flames are better suited for non-selective flaming with covered flamers.

Some burners, with the air inlet close to the nozzles, designed to be operated as open burners, cannot easily be used on covered flamers. An inappropriate positioning of the burners and the cover can lead to oxygen deficiency and thus affect the combustion (Laguë *et al*, 1992). Some covered flamers, therefore, use specially designed burners with the air inlet positioned at a distance from the nozzle and above the cover (Flamers No. 1 and No. 5 in Paper V).

Commercials flame weeders usually have standard atmospheric burners without forced air assistance. These propane burners commonly produce a measurable flame temperature of 1200-1350°C (own measurements). Several technical factors influence the performance of the flame (Lewis & von Elbe, 1987). The flame temperature can be increased by using air-assisted burners (Vriesema, 1985). The reason why such air assisted burners are not used in practice is probably that they would make the flamers even more expensive. Another option is to use other fuels.

Burner setting

There is a lack of consistent knowledge on how to adjust and improve the performance of a flame weeder. The burner setting affects how the flame reaches the weeds and for how long a high temperature is maintained. The appropriate height and angle of the burner are influenced by many factors, including burner type, fuel pressure, flame length, surface conditions, weed height, ground speed and wind. In interaction between burner height and burner angle was found by Storeheier (1991, 1994).

Burner height

There is an optimum range of the burner height for each burner. If the burner is set too close to the ground, the flame will deflect upwards, especially if the burner angle is steep and the fuel pressure high. If the burner is set too high, the hot part of the flame will not reach the weeds. Parish (1989a) found decreased plant reduction with increasing burner height, in the range from 7.5 to 12.5 cm. The strong burners with long flames widely used in the USA in the past, were usually set at a burner height between 15 and 18 cm at an angle of 30 to 45° to the ground (Liljedahl et al., 1964; Parker et al., 1965). However, burners with a short flame require a lower burner height if the hot part of the flame is to reach the ground.

In the present study, the burners in the covered flamers were used at the fixed height determined by the manufacturer, which was between 5 and 15 cm for the different flamers (Paper V).

Burner angle

The appropriate burner angle is different depending on the burner and the adjustment. For the standard Reinert burner, an open flamer commonly used in some parts of Europe, Hoffmann (1989) recommends an angle of 45° at a burner height of 12 cm for flaming preemergence of the crop.

In Paper III, the effects of burner angle were studied for an open burner similar to the Reinert burner. A burner height of 10 cm was chosen, similar for all burner angles, based on the recommendation by Hoffmann (1989) and on preliminary trials. A burner angle of 67° directed backwards showed the highest weed reduction, but there were no significant differences between the effects of the different burner angles. The higher weed reduction at an angle of 67° backwards supports the visual field observations during flaming, which showed that the flame *in operation* hit the ground and then flattened out with little deflection upwards. When the flamer was steady, however, a burner angle of 67° caused considerable flame deflection upwards.

Inconsistent results concerning the appropriate burner angle are commonly reported in the range from 22 to 90° (e.g. Hege, 1989, Lien *et al.*, 1967; Parish, 1989a; Perumpral *et al.*, 1966; Storeheier, 1991, 1994), which may be a result of interactions between different factors. For example, Lien *et al.*, (1967) recommends a burner angle of 30-45° under normal conditions, but a steep angle up to 80° when tall weeds are treated.

American authors often recommend a burner angle of 30 to 45° to the ground, for so-called cross flaming, where open burners were set perpendicular to the travelling direction for selective flaming in row crops (Carter *et al.*, 1960; Smilie & Thomas, 1960; Perumpral *et al.*, 1966; Lien *et al.*, 1967; Kepner *et al.*, 1978). These burner angles have also been used for selective flaming in Europe (e.g. Ascard, 1989; Vester, 1987a, 1987b). However, the American recommendations on flame weeding from the 1950s and 1960s, are not necessarily relevant today.

The use of flame weeding in Europe today, with mainly non-selective flaming of small weeds, is different from the selective flaming of larger weeds in the USA in the past.

Burner power

Burner power in this context means fuel input in terms of kW per metre working width, but it is here also expressed as the propane input in kg h^{-1} m^{-1}. One kg h^{-1} m^{-1} corresponds to 12.8 kW m^{-1}.

The burner power of a flamer can be increased by adding more burners to a given working width. The fuel consumption of a burner can be increased by raising the fuel pressure and by using larger nozzles. The fuel consumption increases with the square of the diameter of the nozzle and with the square root of the fuel pressure (Hoffmann, 1989). Higher fuel pressures or nozzles with larger diameters produce more heat farther away from the nozzle tips. Low fuel pressures as well as smaller nozzles produce flames that are more wind sensitive (Laguë *et al.*, 1992). In practice, change of nozzle size, usually by change of burner, has the greatest influence on the burner power.

The fuel pressure can only be varied within a limited interval. Thus, changes in the fuel pressure have relatively little effect on gas consumption and weed kill by flame, especially with some self-vaporizing burners (Matthews & Tupper, 1964). In dense weed areas, however, flame penetration is improved by higher pressures (Thomas, 1964). In selective flaming, higher fuel pressures may result in less efficient weed control because the increased flame velocity pushes the heat across the row to the next middle (Thomas, 1964).

The results in this study indicate that the effective ground speed generally increases with increasing burner power of the flamer. By raising the fuel pressure from 0.15 to 0.30 MPa, the effective ground speed increased by 40 % for smaller plants with 1-2 true leaves, with an increase in the effective dose of 11% (Paper IV). For larger plants, the effective ground speed was increased by only 17%, and as a result the effective dose was 31% higher at 0.30 MPa than at 0.15 MPa. The lower energy-efficiency at the highest fuel pressure was probably caused by exceeding the optimal fuel pressure.

The effective ground speed was generally higher for flamers with a higher fuel input. A covered flamer, with a propane consumption of 34 kg h^{-1} per metre working width (430 kW m^{-1}), allowed an effective ground speed of 7.9 km h^{-1} to achieve a 95% weed control, whereas the effective ground speed was 2.6 km h^{-1} for a flamer with a burner power of 12 kg h^{-1} m^{-1} (154 kW m^{-1}). Among the covered flamers with a propane input between 7 and 42 kg h^{-1} m^{-1} (90-540 kW m^{-1}), there was no clear indication of a generally poorer energy efficiency of the more powerful flamers, although the relative performance of the individual flamers was dependent on plant size (Paper V). However, it seems that there are no benefits achieved in increasing the burner power above a certain level, if the optimum fuel input of the burner is exceeded. A flamer with a very high propane input of 62 kg h^{-1} m^{-1} (800 kW m^{-1}) showed lower energy efficiency than a flamer with a propane input of 34 kg h^{-1} m^{-1} (430 kW m^{-1}) (Paper V). These results agree with thermodynamic modelling by Bertram (1991), which indicates that for a given type of flamer, there is an optimum fuel input. The upper level is probably influenced by several factors including burner type and design of the flame cover. Thus, major changes to the fuel input of a flamer may have to be followed by change of burner type as well as modifications of the burner setting and cover design (Storeheier, 1991, 1994).

Generally, the results concerning the influence of burner power on the energy efficiency and effective ground speed are contradictory. Several studies have shown increasing weed control with increasing fuel input, regulated by fuel pressure or burner type (Lien *et al.*, 1967; Castille & Ghesquière, 1985; Parish, 1989a, Rahkonen & Vanhala, 1993). Thermodynamic modelling by Bertram (1991) showed an almost additive effect on the heat transfer rate of increased fuel input in the range of 50 to 100 kg propane ha^{-1}. Klooster (1983) and Vester (1987b, 1988, 1990) showed that flamers with high burner power gave similar or better weed control per unit propane than burners with lower power. Storeheier (1991, 1994), however, found poorer performance of higher burner power, in terms of temperature sum per unit propane, in particular for a cover height below 10 cm.

Information gathered from the literature indicates a relationship between burner power and effective ground speed. When flaming was widely used in USA during the 1950s and the 1960s, rather strong burners were used, with an LPG consumption of 4-10 kg h^{-1} (Parker et al., 1965; Lien *et al.*, 1967; Kepner *et al.*, 1978), which corresponds to a fuel input between 30 and 70 kg h^{-1} per metre flame width. These powerful flamers allowed effective ground speeds between 4 and 13 km h^{-1}, depending on burner power and treatment conditions (Liljedahl *et al.*, 1964; Anderson *et al*, 1967; Lien *et al.*, 1967; Matthews & Smith, 1971). When liquid propane spray was used, effective ground speeds up to 24 km h^{-1} were reported (Pivonka, 1968). Today, flamers often have lower burner power. European commercial flamers usually have a fuel input between 10 to 25 kg h^{-1} m^{-1}, which allows effective ground speeds in the range of only 1 to 4 km h^{-1} (Ascard, 1988, Hoffmann, 1989). However an experimental flamer built by Vester (1987b, 1988, 1990) gave an effective ground speed of 9 km h^{-1} at a burner power of 45 kg h^{-1} m^{-1}. This is the same flamer as Flamers No. 3 and 4 in Paper V, although the burners were different.

The increased effective ground speed with increased burner power can be explained by the fact that as the fuel pressure and number of burners increases, the gas velocity and energy density also increase and thereby more heat will be transferred from a dynamic flame through forced convection to the plants at any given time.

Speed of application

Greater changes in weed control effects are achieved by varying ground speeds than by varying rates of fuel pressures with the given burner. The effective ground speed depends on the treatment conditions (plant species, developmental stage, weather) and the flame weeder (burner power, burner type, cover design etc.).

The results mentioned above indicate that the effective ground speed generally increases with increasing burner power of the flamer. However, contrary to these findings, Carter *et al.* (1960) found that the period of time the plant is exposed to the flame, rather than the fuel input was the decisive factor for plant damage. This conclusion was based on experiments with tall cotton plants with corky layers on the stem, treated with open flame burners perpendicular to the row. Little or no adverse effects could be seen when fuel rates varied between 2.9 and 6.5 kg h^{-1} at a ground speed of 4.8 km h^{-1}. At this speed, an individual cotton plant is exposed to the high temperature for about a tenth of a second. However, when speeds were reduced to 3.2 km h^{-1}, serious damage to plants occurred at all fuel rates. The great importance of the exposure time for the cotton stem can be explained by a low heat transfer coefficient for this relatively thick and corky cotton stem. Therefore, a long exposure time is needed to transfer heat by conduction from the surface to the sensitive cambium layer (Mayeux *et al.*, 1968; Bertram, 1994). Thus, when an open burner is used perpendicular to the row, the higher energy input cannot be utilized as it is in the "oven" under a covered flamer.

Single and tandem burners

By using multiple burner rows, the exposure time for the heat and thereby the weed control can be assumed to increase. Porterfield *et al.* (1971) and Vriesema (1985) showed that when tandem burners were used, both the maximum temperature and the duration of high temperatures were considerably increased by using tandem burners instead of single burners. Harris *et al.* (1966) found no increase in the maximum temperature but a considerably increased duration of the heat treatment when tandem or triple burners were used instead of a single row of burners. D'Hulster (1985) reports that the effective ground speed was on average 4 km h^{-1} with tandem burners as compared to 3 km h^{-1} with single burners. Loewer & Mayeux (1970) concluded that tandem burners were superior to a single burner, in terms of the percentage of dead seeds at similar ground speed. However, none of the five above mentioned studies showed whether two-stage flaming was more or less fuel efficient than ordinary one-stage flaming.

The results in Paper IV showed that the effective ground speed was not increased when tandem burners instead of a single burner row were used on a covered flamer. This was most probably a result of an insufficient increase in the temperature and exposure time of the front burner row, due to a relatively low burner power of the first burner. The lethal dose was therefore significantly lower when only one burner row was used.

The results partly agree with those of Loewer & Mayeux (1970); although they concluded that tandem burners were superior, a closer look at the data actually shows a slightly lower weed control at a similar dose and thus a lower energy efficiency of tandem burners, as compared with a single burner.

Open and covered flamers

Flamers with covered burners are generally more energy-efficient and have higher operational safety than open burners (Luttrell & Bennett, 1968; Klooster, 1983; Vester, 1985; Geier, 1987), although the difference is seldom quantified in terms of effective dose or ground speed.

Thermodynamic modelling by Bertram (1991, 1992) suggests that for a standard open flamer at a propane input of 50 kg ha^{-1}, only about 15% of the combustion heat is actually transferred to the plants. For a standard covered flamer, however, the heat transferred to the plants is 30%, and with an optimal cover it can be increased to 60%, according to the model. However, the performance of different open and covered flamers differs greatly depending on several factors such as burner type, burner position, cover design (Klooster, 1983; Vester, 1988, 1990; Bertram, 1991; 1992; Storeheier, 1991, 1994; Vriesema, 1985).

The covered flamers were generally more energy-efficient than the open flamer (Paper V). The open flamer required, on average, a dose 40% higher than that of the covered flamers to achieve good control, although there was a large variation from no difference up to the double-dose requirement. The advantage of using a covered flamer was small when sensitive weeds at early stages were flamed, and greater for tolerant species and larger plants. The performance of the covered flamers depended on the developmental stage of the plants. One flamer was relatively more effective on smaller plants, whereas another flamer was better on larger plants. The difference between the flamers cannot be attributed to the cover only, as the burners and burner arrangements were also different, but the results still indicate opportunities to lower the energy requirement by improving the design of a flamer.

Although covered flamers show several advantages, the use of covers may also involve problems such as oxygen deficiency in the propane combustion. Different flamer designs with or without air fans have been tested, however, with varying results (Luttrell & Bennett, 1968; Hansen, 1969; Luttrell & Gordon, 1969, Vriesema, 1985). Several other factors such as height, length and angle of the cover, also influence the performance of a covered flamer (Storeheier, 1991, 1994).

Temperature measurements

Temperatures in the plant

Accurate measurement of leaf temperatures during flame treatment is very difficult as the temperature changes very rapidly. Thermocouples are commonly used in this type of measurement. Several measuring errors may be involved as any sensor attached to or inserted in a thin leaf will itself act as a heat sink. Moreover, the temperature recorded will be affected by where, in the living plant, the sensor is placed. That data on lethal leaf temperatures during flame treatment are few and inconclusive is probably a result of these factors. Other methods can also be used to measure leaf temperatures. Infrared camera detection has been tested (J. Rahkonen, University of Helsinki, pers. comm.), but the response time of this technique is rather slow. Other researchers have used temperature sensitive lacquers (Anderson *et al.*, 1967).

Lethal leaf temperatures in the range from 55 to 94°C are commonly reported (Anderson *et al.*, 1967; Daniell *et al.*, 1969; Hoffmann, 1989). The temperature in a leaf will not exceed 100°C as long as moisture vaporises from the leaf surface. According to Thomas (1967), the moisture vaporization from the surface forms a very thin protective or cooling film which prevents a rise of temperature above about 93°C at the surface of a living succulent plant. As a normal flame treatment does not burn, but rather blanches the plant tissue, leaf temperatures above 100°C such as those reported by Albrecht (1985), Hege (1989) and Hoffmann (1989) are probably a result of measuring errors.

On the other hand, when thermocouples are placed in a relatively thick stem (e.g. Hansen *et al.*, 1970), lower temperatures will be recorded in the centre than at the edges (Bertram, 1994), and such results may not be relevant for determining lethal temperatures in thin leaves.

Thomas (1964) reported that an exposure to the flame of between 0.065 and 0.13 s has been assumed to be adequate to kill all weeds encountered in a crop although an extremely wide range of weeds were considered. This range of exposure time is, however, based on calculations of the actual exposure time of an 18 cm wide flame, perpendicular to the operating direction, at ground speeds between 4.8 and 9.6 km h^{-1}.

Temperatures in the flame

Many researchers, myself included, have avoided the problem of measuring the leaf temperatures during flame treatment and instead measured the temperatures in the vicinity of the plants or in an environment without plants. As there is no significant vaporization from a thermocouple, the temperatures in the thermocouple will rise considerably higher than 100°C.

In a stationary propane flame, temperatures can reach 1900°C (Lewis & von Elbe, 1987), although considerably lower temperatures in the range from 1200 to 1350°C are usually measured by thermocouples. In a dynamic flame, however, lower temperatures will be recorded, due to the slowness of a thermocouple. Moreover, longer exposure times than, for example, the above-mentioned 0.13 s will be recorded. The deviation from the true temperature is dependent on the time constant of the thermocouple. For example, for a dynamic open flamer in Paper III, a temperature peak of 960°C was recorded when the rear part of the flame passed the thermocouple (Fig. 5). This occurred after 0.5 s at a ground speed of 3 km h^{-1}. After this peak, the remaining part of the temperature-time curve represents the cooling time of the thermocouple, resulting in an "exposure time" above 200°C of 1.8 s. Thus, temperatures recorded by the thermocouples represent neither the temperature in the plant nor in the air but in the thermocouple itself. Thin thermocouples will, however, measure temperatures from a dynamic flame that are reasonably close to the air temperature and thereby related to the convective heat transfer rate to the plants.

Results from temperature measurements in the laboratory, such as those by Perumpral *et al.* (1966), with stationary flames on artificial weed-free surfaces and with the lowest thermocouples 2.5 cm above the surface, are not necessarily valid under conditions in a windy field when small weeds are being treated. The focus on temperature patterns in the air, from 2.5 to 20 cm above the surface was relevant at the time when the main use was selective flaming of established weeds in row crops, where a heat deflection upwards was detrimental. The temperature pattern at the surface level, where cotyledon weeds are found, and the effect of different burner angles on weeds were, however, not studied. Moreover, the movement of the flame in operation will in itself affect the flame pattern.

Relation between temperature and weed control

Several attempts have been made to evaluate flame weeder design by measuring flame temperatures (Carter *et al.*, 1960; Perumpral *et al.*, 1966; Harris *et al.*, 1966; Hassan *et al.*, 1967; Klooster, 1983; Vriesema, 1985; Storeheier, 1991, 1994), although the correlation between these temperature measurements and the weed control is poorly understood.

Few basic results are available on the relation between increasing temperatures measured from dynamic flamers and weed control. Some American researchers used thermal weeders constructed as hot air ovens, in which plants were exposed to a known air temperature for a specified length of time. Response surfaces which were developed show the combination of temperature and exposure time required to obtain a certain degree of plant damage (Batchelder *et al.*, 1970; Lalor & Buchele, 1970; Bashford *et al.*, 1972). However, in these experiments, the temperatures were considerably lower and the exposure time longer than in normal flame treatments. The authors mentioned above used temperatures from 93 to 454°C and exposure times from 0.14 to 6 s. Storeheier (1991) used a similar method for flame treatment, in which plants were moved at different speeds through a stationary flame.

In the present study, another approach was used; temperatures from dynamic flamers in the laboratory in weed-free conditions were recorded by thermocouples. From the resulting temperature-time curves, a number of thermal parameters were calculated, i.e. the maximum temperature, and the temperature sum and time, during which a certain temperature was exceeded. These thermal parameters were correlated with the weed control obtained in the field.

This approach is related to the method used by Rahkonen & Vanhala (1993), who showed an s-shaped relationship between the maximum temperature measured in the vicinity of the weeds and the weight reduction of the weeds.

Effects of different burner angles

When the effects of different burner angles were evaluated, there was a poor and non-significant correlation between the different temperature parameters obtained in the laboratory and the weed control in the field (Paper III). The maximum temperature in particular was poorly correlated with the weed control as the burner angle of 45° directed forwards showed high maximum temperatures in the laboratory but relatively low weed control in the field. However, in this particular study, one cannot expect a high correlation between temperature parameters and the weed control, as there were no significant differences between the effects of different burner angles on the weeds.

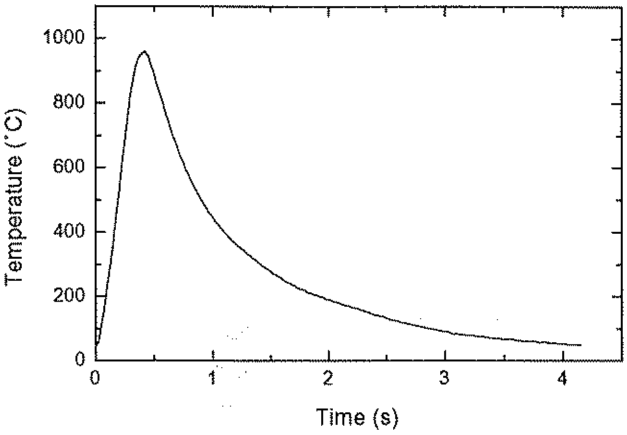

Fig. 5 Temperature-time curve obtained from a dynamic open flamer at a ground speed of 3 km h^{-1} and at an angle of 45° aimed forwards. The maximum temperature at 0.5 s was recorded when the rear part of the flame passed the thermocouple.

Discrepancies between laboratory and field results have also been found by Smilie & Thomas (1960), who found that a burner angle of 22.5° gave the best flame pattern in the laboratory, whereas field tests showed better weed control at a 45° angle.

The weak correlation does not mean that temperature measurements are not useful in flame weeding research, but rather that the research methods have to be improved. If the purpose is to evaluate the appropriate burner angle for field use, one probably either has to do the experiment in the field or create the field conditions in the laboratory.

Effects of type of flamer and increased propane dose

The correlation was generally high between the thermal parameters and the weed reduction, especially when maximum temperature and temperature sum were used (Papers IV and V). The correlation was slightly weaker between the exposure time and the weed reductions. The generally high correlation between the thermal parameters and the weed control, agree with the results of Harris *et al.* (1968), who for insect control, found similar correlation between either maximum temperature, temperature sum or exposure time and the percentage of alfalfa infested tips.

No single thermal parameter showed the highest correlation with the weed control throughout this study. In several experiments, however, the maximum temperature generally showed the highest correlation with the fresh weight reduction in smaller plants, whereas the temperature sum generally showed higher correlation with the reduction in larger plants. There were generally no major improvements in the correlation when the temperature sum was calculated above 400°C instead of above 100°C (Papers IV and V). In fact, the temperature sum above 400°C was not always useful in the correlations, as even temperatures below 400°C corresponded to significant reductions in smaller plants. However, for the reduction in the number of larger plants, the correlation was generally higher when the base temperature 400°C was used. Further research is needed to define the most important thermal parameters.

The sigmoidal relation between maximum temperature and weed control showed that an increasing maximum temperature corresponds to an almost linearly increasing weed control only up to a certain temperature or temperature sum, above which there is little increase in weed control. For example, this upper temperature was about 700°C for weed mixtures in early stages (1-4 leaves) and 900°C in later stages (6-12 leaves), when 0.25 mm thermocouples were used (Paper V). However, these temperature levels differed depending not only on the species and developmental stage, but also on the thickness of the thermocouple. A maximum temperature of 700°C recorded by the 0.25 mm thermocouple corresponds to about 900°C with the 0.13 mm thermocouple. It is therefore impossible to define a general temperature or temperature sum to be reached in order to achieve sufficient weed control.

Klooster (1983) also found generally increased weed control as the flame temperature and the exposure times increased, although the relative importance of these factors was not investigated. The results of Klooster (1983) and Vriesema (1985) indicate that temperatures between 800 and 1000°C lasting for about one second were needed to obtain good weed control. Such indications of temperatures and exposure times are, as mentioned above, strongly dependent on the thickness of the thermocouple. For example, when temperatures were measured from a flamer at a ground speed of 2 km h^{-1}, giving 95% weed control (Fig. 11 in Paper IV), the maximum temperature obtained by 0.13 mm thermocouples reached 960°C and the temperature above 800°C lasted for almost 1 s, which agrees with the results mentioned above. However, when the temperatures were measured by 0.25 mm thermocouples, the same flame treatment resulted in a maximum temperature of only 700°C, which did not agree at all with the results of Klooster (1983) and Vriesema (1985).

Significance of temperature measurements

The maximum temperature measured in the air is related to the convective heat transfer rate to the plants. More precisely, the convective heat transfer rate is linearly related to the temperature difference between the air and the plant. In this study, however, it is of no importance to the correlation if the maximum temperature itself or the maximum temperature minus the temperature in the laboratory (20°C) is used. Moreover, the experimental error in these measurements was such that the temperature difference between two replicates was often in the range from 20 to 100°C.

The temperature sum also takes into account the duration of the thermal treatment and is therefore probably a better measure of the amount of heat applied to the point of measurement and to the possible heat transfer to the plants, at least when the temperatures are measured by thin thermocouples. However, the maximum temperature often gave similar or higher correlation with the weed control than the temperature sum did, particularly when the temperatures were measured by the thicker 0.25 mm thermocouples (Papers IV and V). This may be explained by the way the temperature sum was calculated from the temperature-time curve. A large part of the temperature sum corresponds to temperatures that are considerably lower than the maximum temperature and that were recorded after the actual thermal treatment, when the temperature in the thermocouple dropped to the air temperature in the laboratory. Since higher temperatures are more effective than lower for weed kill (Batchelder *et al.*, 1970; Lalor & Buchele, 1970; Bashford *et al.*, 1972; Storeheier, 1991), this may be why the temperature sums sometimes correlated less with the weed control than did the maximum temperature.

The results were influenced by the height above the ground where the temperatures were measured. For example, the correlation between the temperatures and the reduction in larger (taller) plants was significantly improved when the temperatures were measured at a height of 3.5 cm instead of 1 cm (Paper V). The measuring height was also important when different types of flamers were evaluated. For example, flamer No. 2, which acts largely by infrared radiation, gave a lower temperature sum per unit propane than other flamers at a height of 1 cm (Fig. 10 in Paper V), although this flamer effectively controlled plants in the field (Fig. 6 in Paper V).

There were no consistent differences between the correlations using thermocouples with a diameter of 0.13 mm and 0.25 mm. Therefore, the more robust 0.25 mm thermocouples seem to be more useful in flame weeding research owing to their greater durability.

The sigmoidal relationship between the temperature and the weed control agrees with the results of Rahkonen & Vanhala (1993). A principal difference, however, is that they measured the temperatures in the vicinity of the weeds simultaneously with the flame treatment of the weeds, whereas in this study, the temperatures were measured in a weed-free environment. This is probably the reason why Rahkonen & Vanhala (1993) generally obtained lower temperatures. The higher correlation in this study is partly because different models were used for curve fitting and partly because the correlation was done on the average temperatures of two replicates versus the estimated response according to the speed-response curve. Some of the variation was thereby reduced in the analyses.

The high correlation between the thermal parameters and the weed control is also partly a result of the wide dose range used in these experiments. Several smaller differences observed in the field, in particular not those between different types of flamers, could not be explained by the temperature measurements. There are several reasons for these discrepancies. Although this experimental method is quite common in flame weeding research, the use of naked thermocouples in the laboratory is probably not the best method to model the response of a plant to a flame treatment in the field. Several measurement errors may also be involved in this type of measurements (Doebelin, 1990). Moreover, the laboratory conditions in the rail track with no plants, no wind and a smooth surface are very different from the field conditions. Thus, evaluating flamers based on temperature measurements is a questionable method when knowledge about the relationship between temperatures and weed control is lacking.

Temperature measurements seem to be useful in flame weeding research, although improvements in the experimental methods are needed as is a better theoretical understanding of the relationship between temperatures and weed control.

Environmental impact

The main reason for using flaming is perhaps to avoid chemical herbicides, and thereby eliminate the risk of chemical residues in soil, water and in the crop. However, flaming is generally assumed to require too much energy to play a significant role or even be justifiable in future sustainable farming systems. It is true that flame weeding is energy-requiring in comparison with mechanical and chemical methods (e.g. Ascard, 1988; Casini *et al.*, 1993). In potato production, a broadcast application of flaming requires about ten times more energy than do mechanical and chemical methods for weed control (Fykse, 1985a) and haulm killing (Jolliet, 1993). Such calculations should, however, not be generalized as the energy input will vary largely both within and between crops, depending on, for example, herbicide and application method (Pimentel, 1992).

A broadcast application of flaming, at a propane dose of 50 kg ha^{-1}, corresponds to an energy content of 2300 MJ ha^{-1}. If the energy for transport and processing of propane is added as well as diesel fuel for the application of flaming, the energy use will be about 2700 MJ ha^{-1}, according to Jolliet (1993). In practice, many growers use banded application of flaming and can thereby reduce the fuel consumption considerably. In row crops, flaming can be restricted to a narrow strip over the row, since weeds between the rows can be mechanically tilled very close to the row (Ascard & Mattsson, 1993). Further development of preventive measures (e.g. Ascard, 1994) may even replace the need for flaming in some crops.

Compared with other thermal weed control methods, flaming requires less energy than freezing (Larsson, 1993) and microwaves (Mattsson, 1993), but generally more energy than electrical weed control using the electrical discharge system (Kaufmann & Schaffner, 1982; Vigneault *et al.*, 1990).

Although flame weeding is an energy-requiring method, it should be viewed on the farm level. Flaming is not, and will never be, the principal means of weed control. In agriculture, flame weeding is used mainly in so called minor crops such as vegetables. Flaming is then used when mechanical methods are less effective and chemical herbicides not available due to legislation or consumer demand. Flaming is then often applied once only and further weed control is carried out by mechanical and manual methods.

On the farm level, the total energy used to produce, for example, a maize crop is, according to Pimentel (1992), 47 900 MJ ha^{-1}, and a major component of that support energy is nitrogen fertilizer (13 400 MJ ha^{-1}). Even in a crop with a lower nitrogen requirement such as carrots, a nitrogen fertilization of 100 kg ha^{-1} corresponds to about 6 000 MJ ha^{-1} (Loomis & Connors, 1992), and thereby far exceeds the energy use of a broadcast application of flaming.

In the production of beet sugar, the total energy requirement for growing sugar beets is only about 22% of the total energy requirement for the production of sugar, i.e. 11 200 MJ per tonne sugar (R. Olsson, 1995, pers. comm., Danisco Sugar AB, Sweden). Based on these figures, one banded application of flame weeding pre-emergence of the crop will require about 5% of the energy used for sugar beet growing and only about 1% of the total energy used for the production of sugar.

Even though the combustion of propane is clean in comparison with most fossil fuels, there is generally more air pollution with flaming than with mechanical and chemical methods, according to life cycle analysis conducted by Jolliet (1993). However, the overall load on the environment, including both air and soil pollution, was considerably greater for the chemical method than for the thermal method, and the mechanical methods gave the lowest overall pollution, according to the weighting methods used. Jolliet (1993) also found that the pollution linked to the haulm destruction represents less than 5% of the environmental load during the overall potato production on the farm level. This was compared to the pollution linked to fertilizers, representing 58% of the overall pollution.

Åkermo (1989) reported that even if all potato production in Sweden were flame treated, this would only make up 1% of the total consumption of liquefied petroleum gas (LPG) in Sweden. The total LPG consumption in turn, makes up about 1% of the total combustion of fossil fuels. In terms of carbon dioxide release, this potential use of flaming in Swedish potato production corresponds to the discharge from 250 cars during one year (Åkermo, 1989).

On the food production level, farms produce only the ingredients of most food and additional labour and energy are required for transport, storage, processing, refrigeration, merchandising, and cooking. In industrialized countries, the energy used in this second part of the food production system, far exceeds that used to produce the ingredients at the farm. For example, more energy is consumed in toasting a slice of bread than in growing the wheat it contains (Loomis & Connor, 1992).

On the national level, industrialized societies use 10-15% of the total energy use on their food production systems and 3-5% on the farming component (Loomis & Connor, 1992). Thus, most opportunities to lower the energy use exist not just outside farming, but also outside the entire food production system.

Thus, many factors have to be considered in the evaluation of farming methods. Pollution from chemical pesticides has to be weighed against other types of air, water and soil pollution, as well as the use of natural resources. The result of any environmental impact assessment or life cycle analysis, such as those mentioned above, will depend on the methods used for weighting and comparing different environmental impacts.

Concluding remarks

Summary of findings

Dose-response and speed-response curves

The dose-response concept, known from herbicide bioassay, was developed and applied to flame weeding. Logistic models, that are symmetric on the log dose scale, could generally describe the response of the plants to increasing propane doses. However, in some cases, the logistic models were modified to describe asymmetric dose-response curves (Paper I) and stimulation of emergence at growth at high propane doses (Paper II). A new method for describing the response of the plants to varying ground speeds was developed by a re-expression of the dose-response model (Papers IV and V). By using dose-response and speed-response curves, effective doses and ground speeds can be estimated for different situations, rather than just showing that one treatment is different from the other. It is, however, not possible to give general recommendations about doses based only on a few dose-response experiments. The effective dose may vary considerably depending on species and developmental stage, and may also vary from one experiment to the other (Papers I and II). However, several dose-response experiments carried out under different conditions can form a basis for recommendations dependent on flaming technique, weed flora, stage of development and weather.

Effects on weeds

Flame weeding is mainly effective on small annual weeds. The weed species could be divided into four groups with different susceptibility and dose requirement. The most important factor distinguishing sensitive and tolerant species was not the heat tolerance of the leaves, but rather the ability of plants to regrow after the flame treatment (Paper II). There was a large variation in dose requirement between sensitive and tolerant species, and larger plants needed considerably higher doses than did smaller plants. Split application with two half-dose treatments one week apart did not give a higher weed control effect than a single late flame treatment at the same total dose, when naturally emerged weeds were flamed at early stages. However, split and repeated applications are prerequisites for starving larger plants and heat tolerant weeds (Paper II).

Effects of flamer design

The effects of several flamers and adjustments were evaluated. Inconclusive results were obtained, regarding the appropriate burner angle of an open flamer (Paper III). There was no significant improvement in the effective dose or ground speed when tandem burners, as compared to a single burner row, were used on a covered flamer (Paper IV). By raising the fuel pressure on a covered flamer, the effective ground speed increased; for smaller plants this could be done with only a minor increase in the effective dose (Paper IV). The effective ground speed was generally higher for flamers with higher burner power, but only up to a certain level (Paper V). Covered flamers were generally more energy-efficient than an open flamer, although there was a large variation from no difference up to the double-dose requirement for the open flamer. Covered flamers was used to the greatest advantage on tolerant species and larger plants (Paper V).

Correlation between temperature and weed control

There was generally a high correlation between temperatures obtained from dynamic flamers in the laboratory and weed reduction in the field, although the temperature measurements did not explain all the differences observed in the field (Papers III, IV and V). The sigmoidal relation between maximum temperature and weed control showed that an increasing maximum temperature corresponds to an almost linearly increasing weed control only up to a certain temperature or temperature sum, above which there is little increase in weed control.

Conclusions

Flame weeding is useful in many situations, especially for non-selective weed control, where chemical herbicides are not desired or available, and where mechanical methods and other alternatives are less efficient. Flaming generally uses more energy than chemical and mechanical weed control. Dose-response curves will therefore be useful in future flame weeding research aimed at reducing energy consumption but still maintaining sufficient control. There is potential for adjusting the propane dose to the weed flora and to the stage of development. Further work is needed to determine the dose requirement for different weed species at different developmental stages and under different environmental conditions.

There is also a potential to improve the energy-efficiency and increase the effective ground speed by using properly designed and adjusted flamers. Temperature measurements seem to be useful to evaluate flamer design, but the methods need to be improved. Further development of techniques for thermal weed control is required, based on knowledge of biology and thermodynamics.

The main reason for using flaming is probably to avoid chemical herbicides. The use of flame weeding eliminates the risks of pollution from herbicides, but has other disadvantages such as generally higher costs and high energy consumption. The significance of the energy use, however, depends upon the level on which the comparison is made. Although flame weeding is relatively energy demanding, the energy use for weed control is small compared with that for nitrogen fertilizer and other energy inputs on the farm level. On the food production level, the energy use for producing the food ingredients on the farm is only a small fraction of the total energy use.

From an environmental point of view, soil and water pollution from herbicides has to be weighed against use of fossil energy and air pollution from flaming. Environmental impact assessment and life cycle analysis have to be developed, based on scientific knowledge and political decisions, to form a basis for future work towards a more sustainable society.

Sammanfattning (Summary in Swedish)

Termisk ogräsbekämpning med flamning: biologiska och tekniska aspekter

Termisk ogräsbekämpning är ett samlingsnamn för olika metoder som använder höga eller låga temperaturer eller elektriska fält för att bekämpa ogräs. Det är dock huvudsakligen flamning med gasollåga som har någon större användning idag. Det finns ett förnyat intresse att använda flamning som ett alternativ till kemiska ogräsmedel (herbicider). Flamning skall dock inte blandas ihop med bränning, eftersom man vid flamning endast hettar upp ogräsen så att cellmembraner i växten brister och ogräsplantan torkar ut. Flamning används idag som en integrerad del i ogräsbekämpningen, främst i ekologiskt lantbruk, och används där oftast för att flamma ogräs före grödans uppkomst i morötter och lök och andra långsamtgroende grödor. Andra aktuella användningsområden är ogräsbekämpning på hårdgjorda ytor samt blastdödning av potatis före skörd.

Flamning är användbar i många situationer där kemiska ogräsmedel inte är önskvärda eller tillgängliga och när andra alternativ är mindre effektiva. Fördelar med flamning är att förbränningen av gasol är relativt ren och att man eliminerar risken för föroreningar från kemiska herbicider. Flamning är dock generellt dyrare än kemisk ogräsbekämpning. Metoden är också mer energikrävande än kemisk och mekanisk ogräsbekämpning och medför mer utsläpp av koldioxid till luften. Å andra sidan är energiåtgången för ogräsbekämpning liten jämfört med energibehovet för kvävegödsel och drivmedel i jordbruket.

Det övergripande syftet med detta avhandlingsarbete var att studera inverkan av olika biologiska och tekniska faktorer på effekten av flamning, för att med denna kunskap kunna minska energiåtgången och öka kapaciteten på flamningsutrustningen.

Bekämpningseffekten på små ettåriga ogräs och testväxter undersöktes i fältförsök. Inverkan av gasoldos (propan) och körhastighet på ogräseffekten beskrevs med så kallade logistiska modeller. Med dessa modeller beräknades "effektiva doser" och "effektiva körhastigheter", dvs de doser och körhastigheter som gav god bekämpningseffekt. De s-formade kurvorna för dos-respons och "hastighet-respons" innebär att gasoldosen och körhastigheten kan anpassas till önskvärd bekämpningsnivå, ogräsflora och utvecklingsstadium hos ogräsen. För känsliga ogräsarter i hjärtbladstadiet och upp till 4 örtblad, krävdes gasoldoser på 10-20 kg per hektar för att uppnå 95% bekämpningseffekt, medan det krävdes 20-50 kg ha^{-1} (900-2300 MJ ha^{-1}) för att uppnå 100% effekt. Exempel på känsliga arter är svinmålla (*Chenopodium album*), etternässla (*Urtica urens*) och våtarv (*Stellaria media*). I senare utvecklingsstadier, när dessa ogräs hade 4-12 örtblad krävdes avsevärt högre gasoldoser (50-200 kg ha^{-1}) för att uppnå full effekt.

Relativt höga gasoldoser krävdes också vid flamning av svårbekämpade arter, t.ex. lomme (*Capsella bursa-pastoris*) och gatkamomill (*Chamomilla suaveolens*), speciellt i sena utvecklingsstadier. De mest toleranta arterna, t.ex. vitgröe (*Poa annua*) kunde inte bekämpas fullständigt med en flamning oavsett dos. Detsamma gäller andra gräs och fleråriga rotogräs som kräver upprepade behandlingar för att svältas ut.

Flera flamningsaggregat med olika egenskaper undersöktes. Flammare med inkapslade gasolbrännare var generellt mer effektiva än flammare med öppna brännare, speciellt på större ogräs och vid behandling av svårbekämpade arter. Den effektiva körhastigheten var generellt högre för flammare med hög bränsletillförsel, men bara upp till en viss nivå. En flammare med hög brännareffekt, d.v.s. gasoltillförsel på 34 kg h^{-1} per meter arbetsbredd (440 kW m^{-1}) medgav en effektiv körhastighet på 8 km h^{-1} när mindre plantor behandlades, medan en flammare med mer normal gasoltillförsel på 12 kg h^{-1} m^{-1} (150 kW m^{-1}) endast kunde köras med en hastighet på 2.6 km h^{-1} för att uppnå god bekämpningseffekt.

Temperaturer mättes i flammor och i luften under flamningsaggregaten när redskapen var i drift i en rälsbana inomhus. Det fanns generellt hög korrelation mellan maximumtemperaturen eller temperatursumman, uppmätt från de olika aggregaten i rälsbanan, och ogräseffekten som uppnåddes i fält. Flera avvikelser noterades dock. Temperaturmätningar kan således vara användbara som ett verktyg för att utveckla och testa olika konstruktioner och inställningar hos en flammare, men testmetoden behöver förbättras.

Flamning fungerar alltså som bekämpningsmetod i flera situationer, men metoden kan utvecklas ytterligare. Dos-responskurvor är användbara i framtida forskning och utveckling för att minska energiåtgången, men ändå uppnå fullgod bekämpningseffekt. Mer forskning behövs dock för att fastställa letal dos för olika ogräsarter i olika utvecklingsstadier, beroende på vädersituation. Det finns också stora möjligheter att sänka energåtgången och öka den effektiva körhastigheten genom att använda lämpligt konstruerad och rätt inställd utrustning. Sådan utveckling av teknik för termisk ogräsbekämpning bör baseras på kunskaper i biologi och värmelära.

Vid utvärderingen av olika odlingsmetoder måste många faktorer vägas in. Ur miljösynpunkt, måste i det här fallet föroreningar från herbicider till mark och vatten vägas mot luftföroreningar och ökad förbränning av fossila bränslen vid flamning. Som beslutsunderlag behöver miljökonsekvensbeskrivningar och livscykelanalyser utvecklas och anpassas till jordbruksproduktion. Dessa bör baseras på vetenskaplig grund och politiska beslut för att kunna användas som underlag för fortsatt arbete för ett uthålligt jordbruk.

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A note to the reader: The above-cited proceedings from the First to the Ninth "Annual Symposium on Thermal Agriculture", 1964-1973, are available from the Mann Library, Cornell University, Ithaca, NY, USA. The proceedings from the fourth to the ninth symposium are also available from the Agricultural University, Wageningen, Netherlands.