REVIEW

Hardy herbaceous perennials: A review of techniques for manipulating growth and flowering

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1.0. Introduction

There is increasing scope for sales of quality hardy herbaceous plants, through garden centres and opportunity niche markets (e.g. multiples). This requires attention to detail in the production of batches of quality plants, usually in flower, at target maturity dates, with scope to extend marketing season by manipulation of flowering. Much is known about the manipulation of growth and flowering of protected ornamental plants. Growers of pot, bedding and cut flowers can influence the rate of plant growth and development, and the initiation and expression of flowers, by manipulating environmental factors such as daylength, light intensity, temperature and carbon dioxide concentration. Currently, these factors are being utilised to schedule some perennial plants, but mainly in the sectors that are producing high volumes of fast growing plants from seed, such as *Campanula*. In contrast, hardy herbaceous producers grow a greater range of plants but in smaller numbers, mainly from cuttings.

A wide range of facilities are also used for the production of hardy herbaceous perennials, from specialised near state of the art glass, to less expensive protection where precise control of the environment could prove more difficult to achieve. As a consequence of this, a move towards exerting greater influence over growth and flowering of herbaceous crops could require some capital investment.

Considerable interest has been expressed in the potential for manipulating growth and flowering of hardy herbaceous crops. At present, the natural flowering season of hardy herbaceous subjects is well known but little use is being made of techniques to manipulate flowering, thus extending the season of sale.

However, the production of growing 'blueprints' to schedule species of hardy herbaceous plants could lead to over production and loss of competitive advantage. By developing a screening protocol for use by growers on their own nurseries with their own range of crops, this conflict of interest is avoided.

The objectives of this study were to collect currently available information on crop manipulation techniques, assess which were of practical use for hardy herbaceous production, and develop a screening protocol, for use in on-nursery trialling and/or further R&D.

2.0. What controls flowering in herbaceous perennials?

This chapter covers the basics of plant physiology underlying the processes that lead to flowering in herbaceous perennial species. However, not all herbaceous species behave in the same manner and exceptions are present to most (if not all) rules. This study is not intended to supply information on the cultural requirements of flowering for individual herbaceous species/cultivars, but to outline the factors that can be manipulated by growers to adjust flowering time, and to discuss and propose a screening protocol that will establish for most species the threshold/required parameters to manipulate (force) plants to flower.

A number of perennial species have a **dormant** period, most commonly during the winter. Dormancy is a complex topic (as complex as flowering) with different species responses. Some species need a period of high temperature to end dormancy, others require low temperatures. Photoperiod can also have an effect. However, this review is focussing on influencing flowering in actively growing plant material.

Essentially, the time taken for a plant to flower is the result of environmental conditions during two relatively distinct phases: **flower initiation** and **flower expression**. At its most simple, a period of induction 'switches on' i.e. ***initiates*** flowers, whereas during the period of **expression,** the rate at which buds, and then flowers develop can be influenced by environmental conditions. These two phases can be manipulated independently. An understanding of the physiology of flowering allows the development of a targeted screening system to establish which factors: a) control flowering in certain species and; b) can be manipulated by growers to schedule bud and flower production.

2.1. What influences the initiation of flowers?

A number of environmental factors may be involved in the control of floral initiation:

- Temperature
- Daylength
- Irradiance

However, in *seed raised plants*, a significant number of species have to attain a certain size/age before they will respond to environmental stimuli that promote flowering. This non-responsive phase during which flowers cannot be initiated is termed **juvenility**. Any inductive treatments applied whilst the plant is juvenile will have limited effects on flowering, and are 'wasted effort'. No juvenile phase is reported in the literature for either cutting or division-raised material. However, current MAFF funded work on Lavender (HH1525SHN) has indicated that with micropropagated plant material there may be a non-responsive phase at an early stage of development. Additionally, in woody tree species, delayed flowering has been observed in micropropagated material when compared to seedling raised material. As yet, this has not been explored further. Plant size can also have an effect on initiation. Larger plants tend to initiate flowers more rapidly than smaller plants (of the same species), probably due to the greater area of 'receptive' plant tissue. This response is sometimes described as **Maturity**.

Flowering is essential for the survival of plants *in the wild* and the evolutionary success of these flowering plants has depended largely on their ability to seed. The synchronisation of flowering of plants of the same species has enabled cross-pollination to occur with the least 'wastage' of plant resources i.e. greatest pollination success. Species have evolved differing requirements for the main environmental cues (temperature, daylength and irradiance) that promote flowering. However, the seasonal fluctuations in these cues change with geographical location. The further from the equator, the greater the seasonal variation in daylength and the colder the winters. Plants are adapted to the environmental cues experienced at the geographical location where they evolved. Knowing the geographical location in which a plant evolved, one can often predict the effects of photoperiod and temperature on flowering. For example, a temperate species may require a period of cold followed by long days to ensure flowers are produced during the summer. In contrast, an equatorial plant may flower in short days (~ 12 hours day length) without any requirement for a cold period.

One word of caution to this general rule: the crossing of ornamental plants by man to produce new cultivars and species means that a large element of variation now occurs and *many exceptions exist.*

2.1.1. Temperature

As described above, many plants (though **not all**) require a period of cold for flower initiation. This is sometimes termed vernalisation (Latin derived word meaning 'belonging to the spring'). However, academic definitions vary as a period of cold can have two effects on flowering. It can:

1. make meristems susceptible to conditions that then promote flower initiation

2. directly initiate flowers

Nevertheless, the end result of each mechanism is flowering, and for those species in which this response is found, without a period of cold, flowering may be absent or delayed.

Some plants have an absolute requirement (obligate) and some benefit from (facultative) a period of cold. The cold requirements of plants for floral initiation can be classified as follows:

- Cold is **essential** – plants will only initiate flowers after a critical period of cold (obligate).
- Cold is **beneficial** – plants will initiate flowers without cold, but following a period of cold do so more quickly and/or initiate more flowers and/or initiate flowers more uniformly (facultative).
- Cold is **unnecessary** – little or no benefit is gained from a period of cold.

Plants differ in their requirement (temperature and duration) for cold. It may be thought that the lower the temperature the shorter the period of cold needed to promote flowering. However, the duration of cold (and effectiveness of cold treatment) depends on the plants *optimum* temperature requirement. Many species will require a *greater duration* of cold at temperatures *higher or lower* than the optimum. In general, temperatures close to freezing (< 2°C) are less effective than slightly higher temperatures (2-5°C), and yet higher temperatures will have a reduced effect. As with all plant matters, exceptions exist and many species do not experience 'classical' vernalisation, but initiate flowers at relatively high temperatures (i.e. not requiring a cold store facility).

As well as differing in optimum temperature, species differ in the duration of cold required. Some species require a period of a few weeks (e.g. *Osteospermum*) and others require prolonged periods of time (e.g. *Lavandula*). In general, after a critical period of cold has been supplied, prolonged duration of cold will increase the number of flowers produced up to a maximum. For example, with *Lavandula angustifolia* 'Hidcote', 5 weeks cold (4°C) is sufficient to initiate flowers, whereas 9 weeks cold will give the maximum number of flowers. Further cold has no effect, and will only delay the development of flowers. Ensuring that plants have enough cold to satisfy their requirements for flower initiation is important in practical terms also. Plants that have initiated flowers normally express (develop) flowers faster in warm temperatures. However, where the plants have not received the critical period of cold, flower initiation will be delayed in the warmer temperatures.

2.1.2. Photoperiod

Although plants actually measure the length of darkness, we commonly talk of daylength requirement (photoperiod). As with temperature requirements, plants can be classified on the basis of their response to daylength. Some have an absolute requirement (obligate) and some benefit from (facultative) specific periods of daylength.

- **long day (LD)** plants are plants that only initiate flowers (obligate) –or initiate flowers more readily (facultative)- when the length of the daily light period **exceeds a critical value**.

- **short day (SD)** plants will only initiate flowers (obligate) –or initiate flowers more readily (facultative)- when the length of the daily light period is **less than a critical value**.

- **day neutral** plants initiate flowers readily in **any daylength**

The requirement may differ between species (and cultivars) for the critical daylength as well as the duration of that daylength. The role of daylength is complex. Daylength and temperature often interact; daylength can reduce cold requirement or even substitute for it entirely and cold can alter the photoperiod requirement e.g. change from obligate to facultative response. For example we have shown in *Lavandula angustifolia* 'Hidcote', 5 weeks of constant lighting is sufficient to initiate flowers, without any cold period. However, not all plants respond in this manner and in some plants 24 hour daylength can lead to chlorophyll degradation and a loss of plant quality.

The plants of greatest interest are the LD plants that naturally flower in spring/summer in UK garden conditions, since it is easier to lengthen winter days through lighting, than to shorten summer days (for SD plants) through blackout procedures.

2.1.3. Irradiance

Photosynthesis is the process by which carbon dioxide in the air and water combine to form simple sugars, which are the base units of structural and food materials. This process is driven by light and, when no other factor is limiting, the rates of plant growth and development are related to the amount of light received (**irradiance)**. Essentially, at low irradiances the supply of photosynthates (food and building blocks) is reduced to a level where growth rate may be limited, and this may delay flower initiation. In some species there is a requirement for a critical level of light irradiance, below which flowering is delayed, but this appears to be unrelated to photosynthesis.

2.2. What affects flower expression?

Once flowers are initiated the meristem rarely reverts to vegetative growth, except in extreme conditions. The meristem then develops into a flower bud and then a flower. The conditions that favour the development of the flowers (flower expression) can be the same or different from those required for initiation. Again, plants can be categorised by their responses to the following conditions:

- Temperature
- Daylength
- Irradiance

2.2.1. Temperature

Whereas cold temperatures are often the ideal condition for initiating flowers, generally speaking, warm temperatures increase the rate of flower development. However, these higher temperatures can also reduce the number of flowers and increase stem length, and at very high temperatures the loss of quality may be sufficiently bad as to render plants unsaleable. Consequently, a compromise occurs between speed of flowering and number (and quality) of flowers.

2.2.2. Photoperiod

The same criteria apply for flower expression as for flower initiation:

Some plants have an absolute requirement (obligate) and some benefit from (facultative) specific periods of daylength for the expression of flowers. Again plants can be classified as:

- **long day (LD)** plants are plants that only develop flowers (obligate) –or develop flowers more readily (facultative)- when the length of daily light period **exceeds a critical value**.

- **short day (SD)** plants will only develop flowers (obligate) –or develop flowers more readily (facultative)- when the length of daily light period is **less than a critical value**.

- **day neutral** plants develop flowers readily in **any daylength**

In general, the nearer flowers get to being fully open, the less the importance of photoperiod becomes. The photoperiod requirement for initiation may be independent of that for flower expression e.g. plants that require SD for flower initiation do not necessarily require SD for flower expression. Furthermore, some plants have a dual photoperiod requirement for completion of flowering needing a period of *both* SD and LD.

2.2.3. Irradiance

The physiology underlying the effect of irradiance on flower expression is identical to that influencing flower initiation. Where ambient light levels are low e.g. winter, the rate at which the plant develops flowers may be increased at higher levels of irradiance. Additionally, low light levels may lead to reduced quality in plants being ‘forced’ out of season: higher levels of irradiance may improve quality.

3.0. How can growers manipulate flowering?

3.1. Temperature

Growers can influence plant growth and flowering through temperature: cold can influence flower initiation; increased temperatures can hasten flower expression. Growers are familiar with raising temperatures and encouraging plant growth with glass and plastic structures. The use of cold stores to initiate flowers is perhaps a less familiar approach to many growers in the UK.

3.1.1. Facilities for cold treating plants

Not all herbaceous perennial species benefit from a period of cold. Nevertheless, a number of research organisations, notably Michigan State University (MSU), have been studying the benefits of cold treating plants to hasten flowering. Reading University and HRI are amongst the UK research organisations that have also studied this topic. Much of this work uses controlled environment chambers designed for research purposes to impose fairly accurate cold treatments. Whilst ideal for research, these facilities are very expensive to purchase and maintain, and are not ideal for practical use on growers holdings.

The currently available data refers to cold storing for holding purposes, not for flower initiation (although this may be achieved inadvertently in storing conditions). Information on current cold store use in the ornamentals sector – mainly for holding (often dormant) material prior to marketing, or for batch potting (e.g. Roses) - indicates that growers are using a range of facilities designed originally for storing and/or transporting fresh produce. Nevertheless, the work carried out at HRI-Efford over the last few years has successfully utilised a cut flower cold store for cold treating *Dianthus* and *Lavandula*.

Technical information on the best design and set-up of a facility for cold treating herbaceous perennials specifically is lacking; indeed this issue has not been considered to date. As such, this review outlines the *criteria that need to be accounted for* in the purchase and/or design of a facility for cold treating herbaceous perennials to hasten flowering suitable for use on growers holdings.

The first criterion is the **temperature range** over which the facility will operate. In their screening program MSU run the cold temperature at 5°C, and have had marked success at this temperature with a number of plants. However, as information on optimum temperatures for flower initiation of a range of species is gathered, more effective temperatures, either higher or lower, may be found. A facility that can run at 1 to 10°C +/- 1°C should be ideal. As a minimum the facility must be capable of holding at 4 - 5°C +/- 1°C.

The second criterion is **lighting** in the facility. When storing dormant material, lighting is not an important issue, and material such as bare root roses can be successfully stored in the dark for long periods of time. Experience with seed vernalisation and holding bedding plants such as cyclamen, has shown that low levels of lighting are often sufficient to prevent chlorophyll loss. However, plants *actively growing* at inadequate light levels become etiolated and rapidly lose quality. This is particularly marked with alpine plants in cold stores since they are adapted to grow on at low temperatures. Experience at Efford showed that with *Dianthus alpinus*, although a period of cold (4°C) was beneficial for the flowering of some cultivars, the plants maintained growth in the cold store and, in low light levels, stretched and lost quality.

No studies have been undertaken in the UK on optimum lighting (irradiance or duration) during cold treatment of herbaceous plants. Bedding plants growers holding plants find that cool white fluorescent lights at 200 lux (~0.5 W/m^2) are sufficient for maintaining plant quality in most cases, whereas at MSU the cold facilities are illuminated with cool white fluorescent lights at 750 lux (~2.0 W/m^2). Higher irradiances than 2.0 W/m^2 may be needed, and further study is necessary to establish ideal light conditions in cold facilities to maintain quality. Additionally, the heat load of lights needs considering. Heat build up from lights is minimised by:

a) using low temperature lights such as fluorescent tubes

b) installing the light gearing/ballast outside of cold facilities

c) mounting lights externally and shining through insulated glass

Information on the best daylength for lighting in cold facilities is again limited. Experience at HRI-Efford has shown that daylength whilst cold treating plants can have an influence on the number of flower buds that later develop. Whether this is a response to photoperiod or increased light energy has not been established. At MSU the cold facilities are lit for 9 hours per day. However, chlorophyll breakdown may occur at daylengths less than 12 hours, and plants can become pale, losing quality. A daylength of 12 hours would be prevent this paling, although plants usually recover leaf colour when grown on in ideal conditions.

Whether holding plants or initiating flowers there are a number of potential plant health problems that need to be minimised:

Humidity can be a problem: either too low or too high. With **jacket-type stores** (where the cold air circulates in the wall cavities – the jacket) the air in the store cools and as a consequence relative humidity increases. This, linked with limited air movement may lead to increased incidence of diseases such as ***Botrytis***. The application of fungicides prior to cold treatment may help reduce disease incidence.

In **forced-air stores** (where recirculating air is cooled by a condenser in the store) the problem can be one of **dehydration**. Covering plants with fleece can help reduce the effects of dessication, where this is a problem. Dessication will be greatest where the condenser is having to remove too much heat from the system i.e. is 'working too hard'. It may be that the condenser unit is working at a temperature that is below its optimum and in this case the cooling area of the coil may need increasing. Alternatively, too much heat may be entering the system and it is important to ensure that the wall insulation remains dry and any heat input from lights is minimal. A number of ingenious solutions to the problems of dehydration in forced air refrigeration (such as ice bank refrigeration or zero coolers) are also used in the fresh produce sector. These may be of use in the cold treating of herbaceous perennials depending on the extent of the problem of desiccation. The most cost effective units for growers holdings could depend on what is available on the second hand market!

Prolonged exposure to cold temperatures near to freezing can lead to **chilling injury**, especially with plant tissues in contact with walls or flooring. However, it is anticipated that with *hardy* herbaceous material, optimum temperature for flower initiation should be above that capable of damaging plants.

A number of growers are currently using second hand **refrigerated lorry units/containers**. These are relatively cheap to purchase, can be located quickly (and temporarily if necessary). The installation of lighting is necessary, and electricity would need supplying, but the units are capable of cold treating plants very effectively.

The optimum requirements for cold treating herbaceous perennial plants are not known but it appears that a wide range of facilities can be used successfully. Only further work on, and experience of, these factors will supply the information for growers.

3.1.2. Protected structures

Many HNS growers are now growing plant material under protection for some or all of the production cycle, with an estimated 400 ha of protected HNS cropping in the UK. The initiation of flowers may or may not require a period of cold. Nevertheless, increased temperatures under protection will have a significant effect on plant quality and the speed of flower development in the majority of species.

This review cannot discuss all available protected structures available to growers and their relative merits. However, a brief overview of some of the differences between glass and plastic structures follows.

It is anticipated that the greatest benefit of growing plants under protection will be gained during the colder winter period, as a means of speeding plant development and flower expression for early sales of perennials in bud/flower.

Polytunnels are relatively cheap structures to erect, but it can be more difficult to control the growing environment especially in terms of air movement, than glass. In the cold damp months of winter this can lead to increased incidence of disease associated with high relative humidity, such as botrytis. Another limitation with polytunnels is the often low roof height, making it difficult to install lighting (especially heat generating lights such as SON/T). However, high-sided, single and multispan plastic structures are now available in the UK with novel venting systems and raised guttering that overcome these problems.

Glasshouses can offer good facilities for growers of herbaceous perennials. The improved environmental control can benefit plant growth, keeping the atmosphere drier and reducing the incidence of disease. In contrast to polytunnels, glass structures often lend themselves better to the installation of lighting.

Even without additional heating, glass and plastic structures will raise the temperature of the growing environment. At HRI-Efford during the growing season of 1998-99 the growing environment was on average 1°C warmer in a well vented poly-tunnel, and 3.5°C warmer in an unheated glasshouse than outside. The use of heating will, of course, increase these differences. The individual plant response to temperature is not within the remit of this review, but experimental work has established the flowering time at set temperatures for a number of species. However, there is a trade off with warm temperatures. Plants may develop flowers faster at higher temperatures but can stretch and lose quality with high temperatures and low ambient light levels. Experience will establish the best temperatures environments to aim for.

An interesting area currently being studied in horticulture research organisations is the use of **spectral filters**. In time these may be used more widely for controlling plant growth habit (especially stem length) and these may be ideal for preventing stretching when ‘forcing’ plants to flower. Plant growth regulators (PGRs) may also be of benefit in controlling plant height and HDC have funded studies on this topic (see bibliography).

3.2. Light

Before discussing the options open to growers for manipulating flowering through adjusting daylength and irradiance, a brief explanation of the underlying responses to light is necessary. Light can supply plants with either energy (through **photosynthesis**) or information (**photoperiodism**) or both. The properties of light measured/received by the plants differ in these two responses.

Photosynthesis relies on light absorbed by the chlorophyll pigments in plants. These pigments absorb light across a broad spectrum, with a higher absorption of red and blue light compared to green light, which is reflected (it is this phenomenon that leads to plants appearing green). Additionally, as light used in photosynthesis is the energy input into the system, the amount of light energy (irradiance) is also important and relatively high irradiance is needed by plants for active growth. It is worth noting here that the measurement of light energy is a confusing area! Human vision is most sensitive to a narrow range of wavelengths compared to those wavelengths plants utilise in photosynthesis. Lamp performances are often calculated for the wavelengths humans can see and are most sensitive to (e.g. Lux). However, Lux is an inappropriate unit for measuring light for use by plants as it is the amount of light energy that can be utilised in photosynthesis (termed ***photosynthetically active radiation*** – ***PAR***) that is of importance. This is usually measured as W/m^2 or $\mu mol/m^2/sec$.

In contrast to the chlorophyll pigments, the pigment responsible for **photoperiodic** responses (called ***phytochrome***) absorbs a narrower range of the light spectrum mainly at the red/far-red end of the spectrum, and plants show photoperiodic responses at lower irradiances than those required for photosynthesis. The phytochrome pigment occurs in two forms dependent on light conditions. In daylight the pigment occurs as an active form. During a period of dark, this pigment degrades to the inactive form. What is interesting about this reaction is that light activates the pigment almost instantaneously, but dark leads to a much slower rate of deactivation. It is this slower rate of deactivation that is measured by plants and, although we talk about daylength requirement, plants actually measure the **length of the continuous dark period** rather than the light period.

In summary, plants utilise a ***broad spectrum*** of light of ***high irradiance*** for **photosynthesis**, whereas plants monitor **photoperiod** using a ***narrow spectrum*** of light, and ***low irradiance*** is adequate.

3.3. Controlling daylength

Plant developmental phase often changes in response to changes in photoperiod, especially the change from vegetative to floral growth, and the initiation of flower buds. Compared to the meagre amount of information on the practical aspects of cold treatment of plants, a wealth of information is available on the lighting of plants and their responses. In this review, the plants of greatest interest are the LD plants that naturally flower in spring/summer in UK garden conditions. This requires artificial lengthening of the day *or* shortening of the night.

3.3.1. Day lengthening

The most obvious way of extending day length is by switching on photoperiod lighting either before dawn, or at dusk as the natural daylight diminishes. This can be very effective. However, as the natural day shortens in the winter, the start times for the lights need to be regularly adjusted. The duration of lighting needed to extend daylength depends on the irradiance of light received by the plants and, hence, lamp **energy output** (wattage), **height** over the crop and **distribution**.

3.3.2. Night Interruption / Night Break Lighting

As outlined above, plants measure the period of dark. Consequently, lighting plants in the middle of the night is an extremely effective method of giving long day lighting. This lighting is termed **night break** or **night interruption** lighting (often shortened to NB or NI lighting). Night break lighting has a number of benefits over day lengthening: lighting can be utilised during the cheap night rate electricity period; and one fixed time can be used throughout the period of natural short days, avoiding constant adjustments to a time clock. Additionally, shorter duration of lighting is required than for day extension. For example, to maintain a night length <8 hours in mid winter (natural night length = 14 hours) would require ~ 6 hours day extension or ~ 2 hours night interruption (splitting the night into two dark periods of 6 hours). As with daylength extension, the duration of lighting needed for NB lighting depends on the irradiance of light received by the plants and, hence, lamp **energy output** (wattage), **height** over the crop and **distribution.**

3.3.3. Cyclic lighting

As described previously, light (of the correct wavelength i.e. *red* rather than *far-red*) activates the phytochrome pigment almost instantaneously, and the slower rate of deactivation, that occurs during the dark period, is measured by the plants. This means that regular cycles of light and darkness (**cyclic lighting**) can have the same effect as continuous lighting. This can happen as a small amount of pigment deactivation can occur in a period of dark, with no photoperiodic effect, before the pigment is fully reactivated by another burst of light. An example of cyclic lighting is a cycle of 15 minutes ‘on’ followed by 15 ‘off’ repeated for the duration of lighting, starting and ending with an 'on' period. This system works for both day lengthening and night break lighting. A great benefit of this system is that lights can be lit in sequence reducing the number of lights on at any one time and hence reducing the cost.

3.3.4. Novel systems

With an understanding of the interaction between lighting and plant development, novel approaches to lighting that are more cost efficient may be possible.

For example, by using one lamp of high irradiance, which emitted sufficient light at the red end of the spectrum, it could be possible to achieve cyclic night break lighting over a relatively large area. The lamp could be installed on overhead rails and pulled up and down the length of a greenhouse at a slow rate by an automatic pulley system. Alternatively, for a smaller area, a slowly rotating lamp could be mounted above the plants to be treated, The lamp would need to be angled so that, as it rotated, sufficient light was shining onto the plants. These approaches are theoretical (although anecdotal reports of their use have come from the USA) and would need some development before recommendations could be made.

3.4. Increasing photosynthesis

Where plants are being 'forced' to flower in naturally low winter light levels (through raised temperatures and/or photoperiod lighting) they may become stretched or lose overall quality. In these cases higher irradiance may be necessary to improve flower (and plant) quality. To achieve this, natural daylight can be supplemented with light suitable for photosynthesis (**supplementary lighting**). Different properties are required from the lamps for photosynthesis compared to photoperiod control. Essentially, lamps must produce light across a broader range of the spectrum. Efficiency of running is an important consideration, as higher irradiance output is required for photosynthesis lighting.

In contrast to photoperiod lighting, cyclic lighting is of no benefit with supplementary lighting.

3.5. Types of lights

The placing of lamps is very important to ensure **sufficient light** is delivered. The ideal height above plants and spacing between lamps differs between lamp types and lamp wattage. This information can be found in the technical literature of light manufacturers and other technical reports (see bibliography). A range of lamps are available and this is not an exhaustive review of all possible lamp types. Nevertheless, the more common lamp types are summarised here.

- Incandescent (tungsten filament or GLS)

These lamps are easy to install and maintain, and are cheap to run. They can be suspended in a line (festoon) very simply, and festoons are available with waterproof fittings at set spacings. As the output is very rich in red light they are ideal for photoperiod lighting. However, under incandescent lamps plants can stretch due to the high far-red output. These lamps are not suitable for photosynthesis lighting as irradiance is too low for them to be effective.

- Fluorescent (MCF)

Tubular fluorescent lamps have a large ‘light producing’ area, are efficient and have a low temperature output. The spectral quality of the lamps is adequate for photosynthesis but due to their relatively low irradiance and large size (impeding natural sunlight) are not suited to photosynthesis lighting in greenhouses. Nevertheless, a few growers use ‘compact’ fluorescent lamps for photoperiodic lighting in greenhouses. Additionally, the low temperature output (which allows location in close proximity to the plants) makes them ideal for use in *cold stores* – both for photoperiod and photosynthesis lighting. The lamps take 5-10 minutes before they have ‘warmed up’ and are producing sufficient light. For this reason these lamps are not suited to cyclic lighting.

- SON-T (high pressure sodium)

Probably the most common lamp in horticulture as it is capable of both photosynthesis and (to a lesser extent) photoperiod lighting, has a high radiant efficiency and a long life. However, it requires lamp gear i.e. ballast and ignitor and also a reflector. These are commonly combined together in a single unit called a luminaire. SON-T lamps produce heat, and in a plastic structure cannot be too close to cladding. These lamps are expensive to purchase and it is not recommended that they are installed to provide photoperiod lighting alone – incandescent lamps are much cheaper. Nevertheless, if already available they are capable of photoperiod lighting. As with fluorescent lamps, SON/T lamps take time to warm up before producing sufficient light and are not suited to cyclic lighting.

- Metal Halide (MBI)

These lamps have a very high light energy output and have excellent spectral quality for photosynthesis lighting. However, these lamps are currently much more expensive than SON/T lamps, require a luminaire and their life-span is generally shorter than SON/T lamps.

4.0. Screening Protocols

A large number of questions can be answered through a multi-factorial screening protocol. However, the more factors included in the protocol, the larger and, hence, more expensive the protocol will become. Research style facilities are needed to establish the optimal light and temperature settings for cold stores and growing on environments. Nevertheless, important information, essential for the manipulation of flowers, can be ascertained from a relatively simple screening protocol.

By following the approaches outlined in this review it would be possible to produce growing ‘blueprints’ for the scheduled production of species of hardy herbaceous plants. However, the widespread dissemination of this information could lead to over production of these species and a loss of competitive advantage for individual nurseries. With this in mind the following screening protocols have been designed to be used by **growers on their own nurseries** with their own chosen range of species. This should allow development of scheduled production whilst maintaining confidentiality for the producer of specialist species. Nevertheless, there is still merit in a demonstration of the protocol and further research for the establishment of the responses of some ‘indicator’ species, and this is suggested in the further work section.

It is anticipated that initially these protocols will be undertaken in the **winter months** to produce material in **bud or flower** in **early - late spring**, before the ‘natural’ flowering season of spring or summer. This is because it is relatively simple to impose long days against a background of short days. The same protocols could supply information for the extended production of flowers into late summer/autumn (for those species that cease flowering earlier in the year). However, plant material that has been *overwintered* in an *unheated* structure, or outside, prior to the beginning of any summer screening protocol may already have naturally *initiated flowers*. Delaying the appearance of these flowers could require either short days (requiring blackouts) against a background of long days or else start material maintained in an uninitiated state over winter (e.g. in a heated greenhouse) which can be difficult.

The start point for the protocols is a cold store. However, not all herbaceous perennials that flower in long days require a period of cold for initiation of flowers (see section 2.1.1) – and this can be established through the protocols. For those that do, allowing plants to accumulate cold naturally for a proportion of the winter period may satisfy the cold requirement before they are placed under protection early in the new year (with or without LD lights). This approach may be sufficient and cheaper but will be **less reliable between years** due to the variability in the weather. Alternatively, once the cold requirement is known, it may be possible to allow plants to accumulate cold naturally for a period of time, and then place them in cold store for a short period of time (1-2 weeks) to ensure cold requirement is satisfied prior to growing on to flower.

Where growers wish to apply the necessary conditions and environments on herbaceous perennial species, the requirements first need to be established using robust repeatable methodology. This is the role of a screening protocol.

Realistically, the following questions need answering for individual species:

A. Flower initiation

- Do the plants require cold for initiation?
- What is the duration of cold required?
- Do plants initiate faster/more flowers under long days or short days?
- What level of irradiance is necessary in the cold store?

B. Flower expression

- Does temperature influence speed of flowering?
- Is heating necessary for commercial production?
- Do plants develop flowers faster/more flowers under long days or short days?
- Is supplementary lighting necessary to maintain plant quality ?

These questions vary in their importance in a low cost production system. As more factors are included the level of both complication and cost will increase and the work required to answer all of the above questions would be prohibitive to most nurseries and expensive. It is more likely that a limited screening protocol would identify species worthy of further study and their 'rough' requirements; 'fine' details could then be established through small scale, detailed work.

As it is likely that the screening may only be possible on nurseries for one period of time each year (winter-spring), one large screening programme may provide the same amount of information as two smaller programmes, but in one year rather than two. Consequently, two protocols are presented here: Protocol I and II.

- ***Protocol I***

This is the 'bare bones' protocol to quickly establish the groupings of a wide range of species that may benefit from a cold period and/or adjusted daylength for flower manipulation.

- ***Protocol II***

This addresses the same questions as Protocol I, but also identifies whether additional heating and/or lighting benefits *crop quality*. In essence, Protocol II allows growers to 'pick and choose' the additional options for studying depending on the facilities available to them.

4.1. Questions and Answers

A number of questions will need answering before the protocols can be undertaken – these are included here along with answers!

What species should I study?

It is suggested that herbaceous perennial species that flower in spring/summer would be best suited to scheduling. Compact species that bear attractive flowers would be well suited to the market that will most benefit from scheduling.

How many factors should I include in the protocol?

In general the factors highlighted in the review as influencing flowering fall into two groups: those controlling the presence, or not, of flowers (flower initiation) and those controlling flower development which also have an impact on general plant quality and hence saleability.

The factors that supply information as to whether **flowers can be produced** are the ***essential*** ones. These are:

- Do the plants require cold for initiation?
- What is the duration of cold required?
- Do plants develop flowers faster/more flowers under long days or short days?

The factors that supply information as to whether **saleable plants** can be produced are the ***supplementary*** ones. These are:

- Does temperature influence speed of flowering?
- (if so) Is heating necessary for commercial production?
- Is supplementary lighting necessary to maintain plant quality ?

There are also a number of ***fine tuning*** factors better suited to a 'trial and error' approach (due to the wide range of treatments that need testing to find the optimum), such as:

- Do plants initiate faster/more flowers under long days or short days?
- What is the optimum daylength for initiation?
- What is the optimum daylength for flower expression?
- What are the optimal temperature regimes?
- What are the optimal lighting regimes?

It is suggested that the essential factors are *always* studied, along with those supplementary factors suited to the production capability of the nursery. Fine tuning factors are of benefit when the main responses have been established and need not be included initially.

Do I need a cold store?

It is possible to allow plants to accumulate cold naturally rather than using a cold store. However, it will be difficult to establish plant cold requirement without using a cold store. A basic approach without a cold store would be to sequentially move batches of plants under protection (with and without lights) in December, January and February. This could give valid information for a commercial system but would lack precision.

When should I start cold treatments?

The ideal start date for using the screening protocol to establish **plant requirements** would be October/November. As plants will have accumulated little natural cold prior to this date. This would also allow the 12 week cold treatment to come out into similar conditions as the other treatments. In practice, if aiming for marketing plants in March/April, the start date for cold treatment for commercial production may be December/January.

What age of material should I use?

It is important to consider the 'history' of the plant prior to starting the screening protocol. As plants need to meet quality specifications on size as well as flowers, it may be necessary to manipulate plant growth *prior* to initiation to ensure plants are of an adequate size at flowering. Essentially, the age of material to be used should be guided by plant size. There is little commercial benefit in establishing how to put flowers on an unbranched cutting!.

What size of pot is best?

There is no reason why large pots (and plants) can not be studied as long as the plants satisfy the criteria in the previous answer. A lot will depend on the product specification for the market place. One extra consideration is the limitations of space; under lights or in the cold store.

What P&D regime should I follow?

It is recommended that a preventative botrytis spray is applied to plants prior to moving into the cold store. White fly can be a problem under the lights when growing plants on and at low temperatures, biological control may be limited, so a routine pest spray may be necessary. All other P&D regimes should be as normal for commercial production.

4.2. Protocol I (cold and day length requirements)

This is the 'bare bones' protocol to quickly establish the groupings of a wide range of species that may benefit from a cold period and/or adjusted daylength for flower manipulation.

The following questions are addressed:

- Do the plants require cold for initiation?
- What is the duration of cold required?
- Do plants develop flowers faster/more flowers under long days or short days?

Facilities required

- **Cold store** at 4-5°C lit with fluorescent tubes for 8 hours a day
- **Glasshouse or polytunnel** with **two areas** with the following conditions
    - no lighting (assuming ambient daylength is SD)
    - photoperiod lighting (tungsten filaments) with 2 hours night break lighting (LD)

One way to impose lighting treatments on a limited area in a glasshouse or polytunnel is to separate off the area illuminated by the lights with a thick opaque plastic sheet/curtain suspended such that no light falls on adjacent plants. This method has been shown to be very effective at HRI-Efford when separating small compartments for just this purpose. Alternatively, two similar structures could be used: one with lights, one without lights

Treatments (See Figure 1a)

Cold store for

- 4 weeks, OR
- 8 weeks, OR
- 12 weeks, OR
- No cold treatment.

AND

Under protection with

- long day, night interruption lighting, OR
- no additional light. i.e. unlit, short days

4 x 2 = 8 treatments in total. It is suggested that 10 plants are the minimum needed for each treatment = 80 plants.

Method (See Figure 1a and 1b)

Initially, 80 plants from the same batch should be collected together. Ideally, the plants should be of similar size and age. Plants should be split into four equal batches of 20 plants: Place 60 plants in the *cold store* (4-5°C lit with fluorescent tubes for 8 hours a day). The remaining 20 plants will receive no cold and should be placed *under protection*: 10 under photoperiod lighting (tungsten filaments with 2 hours night break lighting), and 10 without additional lighting.

4 weeks, 8 weeks and 12 weeks after the start take 20 plants from the *cold store*, and place 10 in the area with photoperiod lighting (tungsten filaments with 2 hours night break lighting, and 10 in the area without additional lighting.

It is suggested that plants are labelled either at the start of treatments or as they are moved from the cold store into the growing on conditions. Plants should be observed and recorded frequently, at least weekly, and the day the first bud and flower are observed should be noted. General descriptions should also be recorded. If possible recording temperatures under protection can be useful when interpreting results.

Figure 1a. Experimental treatments

Treatment label	Week number			
	Start	***+ 4 weeks***	***+ 8 weeks***	***+ 12 weeks***
1	SD	SD	SD	SD
2	LD	LD	LD	LD
3		SD	SD	SD
4		LD	LD	LD
5			SD	SD
6			LD	LD
7				SD
8				LD

Figure 1b. Number of plants at each location

Facilities	***Start***	***+ 4 weeks***	***+ 8 weeks***	***+ 12 weeks***
	60	40	20	0
SD	10	20	30	40
LD	10	20	30	40
Total	***80***	***80***	***80***	***80***

Key

	= Cold store at 4-5°C lit with fluorescent tubes for 8 hours a day
SD	= Glasshouse or polytunnel with no lighting (assuming ambient daylength is SD)
LD	= Glasshouse or polytunnel with photoperiod lighting (tungsten filaments) with 2 hours night break lighting (LD)

4.3. Protocol II. (cold and day length requirements, and benefit of additional heating and photoperiod lighting)

This addresses the same questions as Protocol I, but also identifies whether additional heating and/or lighting benefits *crop quality*. In essence, Protocol II allows growers to 'pick and choose' the additional options for studying depending on the facilities available to them.

Heating can allow **finer prediction** of flowering time. Heating and lighting may also have a marked effect on plant quality and hence saleability

The following questions are addressed:

- Do the plants require cold for initiation?
- What is the duration of cold required?
- Do plants develop flowers faster/more flowers under long days or short days?
- Does temperature influence speed of flowering? If so -
- Is heating necessary for commercial production?
- Is supplementary lighting necessary to maintain plant quality ?

Facilities required

- **Cold store** at 4-5°C lit with fluorescent tubes for 8 hours a day
- **Unheated glasshouse** or polytunnel with **four areas** with the following conditions
    - no lighting (assuming ambient daylength is SD)
    - 8 hours supplementary (photosynthesis) lighting (SD)
    - photoperiod lighting (tungsten filaments) with 2 hours night break lighting (LD)
    - 8 hours supplementary lighting and 2 hours night break lighting (LD)
- **Heated glasshouse** or polytunnel with **four areas** with the following conditions
    - no lighting (assuming ambient daylength is SD)
    - 8 hours supplementary (photosynthesis) lighting (SD)
    - photoperiod lighting (tungsten filaments) with 2 hours night break lighting (LD)
    - 8 hours supplementary lighting and 2 hours night break lighting (LD)

One way to impose lighting treatments on a limited area in a glasshouse or polytunnel is to separate off the area illuminated by the lights with a thick opaque plastic sheet/curtain suspended such that no light falls on adjacent plants. This method has been shown to be very effective at HRI-Efford when separating small compartments for just this purpose. Alternatively, two similar structures could be used: one with lights, one without lights

Treatments (See Figure 2a)

Cold store for

- 4 weeks, OR
- 8 weeks, OR
- 12 weeks, OR
- No cold treatment.

AND

Under protection with

- Long days, night interruption lighting, OR
- Short days, unlit

AND

- Heating, OR
- No heating

AND

- With supplementary lighting, OR
- Without supplementary lighting

4 x 2 x 2 x 2 = 32 treatments in total. It is suggested that 10 plants are the minimum needed for each treatment = 320 plants.

Method (See Figure 2a and 2b)

Initially, 320 plants from the same batch should be collected together. Ideally, the plants should be of similar size and age. Plants should be split into four equal batches of 80 plants:

Place 240 plants in the *cold store* (4-5°C lit with fluorescent tubes for 8 hours a day). The remaining 80 plants will receive no cold and should be placed under protection: a total of 40 plants should go into the *heated structure*; 10 without additional lighting, 10 under photoperiod lighting (tungsten filaments with 2 hours night break lighting), 10 under supplementary lighting (8 hours SON/T lamps), and 10 under supplementary lighting (8 hours SON/T lamps) with additional 2 hours night break lighting (SON/T lamps). The remaining 40 plants should go into the same conditions in an *unheated structure*.

4 weeks, 8 weeks and 12 weeks after the start take 80 plants from the cold store, and place under protection: a total of 40 plants should go into the *heated structure*; 10 without additional lighting, 10 under photoperiod lighting (tungsten filaments with 2 hours night break lighting), 10 under supplementary lighting (8 hours SON/T lamps), and 10 under supplementary lighting (8 hours SON/T lamps) with additional 2 hours night break lighting (SON/T lamps). The remaining 40 plants should go into the same conditions in an *unheated structure*.

It is suggested that plants are labelled either at the start of treatments or as they are moved from the cold store into the growing on conditions. Plants should be observed and recorded frequently, at least weekly, and the day the first bud and flower are observed should be noted. General descriptions should also be recorded. If possible recording temperatures under protection can be useful when interpreting results.

Figure 2a. Experimental treatments

Treatment label	**Week number**			
	Start	***+ 4 weeks***	***+ 8 weeks***	***+ 12 weeks***
1	SD	SD	SD	SD
2	SD & Supp	SD & Supp	SD & Supp	SD & Supp
3	LD	LD	LD	LD
4	LD & Supp	LD & Supp	LD & Supp	LD & Supp
5	SD	SD	SD	SD
6	SD & Supp	SD & Supp	SD & Supp	SD & Supp
7	LD	LD	LD	LD
8	LD & Supp	LD & Supp	LD & Supp	LD & Supp
9	CS	SD	SD	SD
10	CS	SD & Supp	SD & Supp	SD & Supp
11	CS	LD	LD	LD
12	CS	LD & Supp	LD & Supp	LD & Supp
13	CS	SD	SD	SD
14	CS	SD & Supp	SD & Supp	SD & Supp
15	CS	LD	LD	LD
16	CS	LD & Supp	LD & Supp	LD & Supp
17	CS	CS	SD	SD
18	CS	CS	SD & Supp	SD & Supp
19	CS	CS	LD	LD
20	CS	CS	LD & Supp	LD & Supp
21	CS	CS	SD	SD
22	CS	CS	SD & Supp	SD & Supp
23	CS	CS	LD	LD
24	CS	CS	LD & Supp	LD & Supp
25	CS	CS	CS	SD
26	CS	CS	CS	SD & Supp
27	CS	CS	CS	LD
28	CS	CS	CS	LD & Supp
29	CS	CS	CS	SD
30	CS	CS	CS	SD & Supp
31	CS	CS	CS	LD
32	CS	CS	CS	LD & Supp

(Key presented overleaf)

Figure 2b. Number of plants at each location

Facilities	Week number			
	Start	***+ 4 weeks***	***+ 8 weeks***	***+ 12 weeks***
CS	240	160	80	0
SD	10	20	30	40
SD & Supp	10	20	30	40
LD	10	20	30	40
LD & Supp	10	20	30	40
SD	10	20	30	40
SD & Supp	10	20	30	40
LD	10	20	30	40
LD & Supp	10	20	30	40
Total	***320***	***320***	***320***	***320***

Key

	= Cold store at 4-5°C lit with fluorescent tubes for 8 hours a day
SD	= Heated glasshouse or polytunnel with no lighting (assuming ambient daylength is SD)
SD & Supp	= Heated glasshouse or polytunnel with supplementary lighting (8 hours SON/T lamps)
LD	= Heated glasshouse or polytunnel with photoperiod lighting (tungsten filaments) with 2 hours night break lighting (LD)
LD & Supp	= Heated glasshouse or polytunnel with supplementary lighting (8 hours SON/T lamps) with additional 2 hours night break lighting (SON/T lamps)
SD	= Unheated glasshouse or polytunnel with no lighting (assuming ambient daylength is SD)
SD & Supp	= Unheated glasshouse or polytunnel with supplementary lighting (8 hours SON/T lamps)
LD	= Unheated glasshouse or polytunnel with photoperiod lighting (tungsten filaments) with 2 hours night break lighting (LD)
LD & Supp	= Unheated glasshouse or polytunnel with supplementary lighting (8 hours SON/T lamps) with additional 2 hours night break lighting (SON/T lamps)

5.0. Concluding statement

Scheduling of plants in flower or bud has the potential to open up a **new market for traditional HNS growers**. The information that can be gained from the results of the protocols will allow growers to establish the environmental 'cues' for flowering. This understanding will enable the grouping of herbaceous perennial species by their responses; e.g. require cold and long days etc. Plants from these groups can then be manipulated to produce flowers over an extended season.

The screening protocols described here are for **use by growers on their nurseries**, with their own range of crops. Through this approach it will be possible for growers to establish the environmental requirements for flowering of their specialist species without the widespread dissemination of growing 'blueprints' and the potential over production and loss of competitive advantage that could be associated with this.

The use of a cold store, a protected structure and photoperiod lighting should be sufficient to manipulate flowering in a large number of herbaceous perennial species. It is envisaged that, initially, the best approach will be to concentrate on LD plants and encourage flowering in early spring, before their natural flowering period. However, further R&D work is needed to 'fine tune' the protocols and also develop the practical application of scheduling techniques to herbaceous perennials. Plants need to meet quality specifications on size and form as well as flowers and it will be necessary to manipulate plant growth prior to initiation to ensure plants are of an adequate size at flowering.

One issue not covered in this review is the **cost benefit of scheduling**. The use of a cold store, lighting and heating is expensive. Unless this increased cost can be recovered (plus more) scheduling will not be a viable system. The increased return can come through:

a) selling products into the market place before cheaper imports arrive in the UK, and/or

b) better use of growing areas, by clearing space earlier in the year allowing an extra crop through.

An important factor in scheduling will be the end market for the products. Again, scheduling is only really viable if customers want to buy the earlier flowering plants. These issues are outside the remit of this review, but must be considered.

6.0. Recommendations for further work

1. The most **immediate** recommendation is for the **testing of the screening protocol** proposed here. This should include up to 10 species (selected by a sub-committee of hardy herbaceous perennial growers) which are representative of a range of expected requirements. This would allow:

a) '**fine tuning'** of the protocol;

b) **practical demonstration** to the industry (technology transfer);

c) an initial **cost benefit analysis** of production costs, and;

d) the **publication** of the findings as a 'base line' database.

2. The approach taken here for hardy herbaceous perennials could also have application to **flowering shrubs**. However, woody species can have complicated floral initiation over relatively long periods of time i.e. with plants flowering on old wood, initiation may occur 6 months before flowers develop. Nevertheless, there would be merit in trying to **develop a screening protocol** for establishing the environmental requirements for flower initiation and development in flowering shrubs**.**

3. Whilst compiling the review it was clear that there are a number of areas in which there is limited or no information to guide growers. This was most notable in the area of cold store facilities. Further **development work** is therefore needed to establish suitable recommendations for:

a) **Cold store type -** what is the most suitable system for cold storing plants at 1-10°C for up to 3 months?

b) **Lighting in cold stores** – what is the most cost-effective system for lighting plants, and what is the light level needed to sustain plant quality whilst cold treating plants?

4. Immediate improvements could be suggested for scheduling techniques through the further study of the control of plant form through the use of **PGRs**, and **Spectral Filters.** HDC funded work has already demonstrated improvements in plant form through the use of PGRs in HNS (HNS 39, 39a & b). Spectral filters are a topic for the future with promising results already emerging for pot plants, cut flowers and HNS. The potential for the use of Spectral Filters lies not only on the manipulation of plant growth, but also in the control of pests and diseases.

There are a number of topics of **strategic research** that would benefit the development of scheduling in herbaceous and woody perennials:

5. Research is needed into the development and production of **pre-determined plugs** that are already partially, or fully induced to flower before delivery to the nurseryman. This would remove the need for cold store facilities on individual nurseries, and could have potential for export markets also. This requires work into the **influence and persistence of partial induction** of flowers.

6. It is clear that **stock plant management** has a major effect on the development of flowers in cuttings. Methods for maintaining un-initiated cuttings would aid consistent flower scheduling between seasons, and also through the year, by removing variability.

7. **Basic scientific research** is still needed into the **plant physiology of floral initiation**. Although a reasonable amount is known about this topic, a deeper understanding of the plant processes may allow the development of new approaches to floral initiation e.g. development of a molecular assay for cold requirement.

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