Biosystems Engineering (2006) **93** (1), 69–80
doi:10.1016/j.biosystemseng.2005.09.007
SE—Structures and Environment

Improved Strategy for a Constant Daily Light Integral in Greenhouses

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(Received 7 February 2005; accepted in revised form 8 September 2005; published online 4 November 2005)

At Cornell University a continuous-mode greenhouse pilot-plant is producing lettuce at a constant rate throughout the year. Plants of all ages, floating on nutrient solution, are present in the greenhouse at any time. They move from the starting point to the harvest point in 24 days, all under the same environmental conditions, repeated day after day throughout the year.

The key to the success of such an operation is a constant daily light integral, which can be achieved only through shading and supplemental lighting. Since the potential loss of yield from insufficient lighting (in winter) and the damage from leaf tip burn (LTB) from excessive light (in summer) are high, a rather tight light control is required, which is currently achieved with a rule-based strategy labelled C. A new strategy N, which tracks a reference light trajectory, is now introduced and compared, *via* simulation, with strategy C, as well as with a reference strategy R, which assumes the availability of a perfect 1-day-ahead forecast of total daily solar radiation.

The results show that all strategies are rather robust to variation among years and among locations (within the US). Strategy N out-performs strategy C on average by about $7\,\$\,m^{-2}\,yr^{-1}$ and does almost as well as strategy R ($1\,\$\,m^{-2}\,yr^{-1}$ difference). All strategies utilise at least some of the economic information contained in the performance criterion, with strategy N more than the others.

The application of strategy N to sizing of the control equipment and to systems with insufficient equipment capacity, is demonstrated.

1. Introduction

Perishable crops are usually marketed at the rate they are produced, and fetch prices according to the prevailing market conditions or according to an agreed contract. A particular example of the latter is a contract to supply equal amounts of produce each day of the year. This can be done either by selling surplus production through less profitable channels, or by targeting production to the daily marketing quota.

A pilot project, aiming at a uniform daily production of hydroponic lettuce, is in operation at Cornell University for the past few years (Both *et al.*, 1999). This project is an attempt to retain the advantages of constant plant production under strictly industrial conditions (the so-called 'plant factory', *e.g.* Nakayama, 1991), while reducing the costs, mainly of light and air conditioning, by replacing the isolated structure by a conventional greenhouse.

Plants of ages 12–35 days, floating on nutrient solution, are present in the greenhouse at any time. They move from the starting point to the harvest point in 24 days (residence time), all under the same environmental conditions, repeated day after day throughout the year. This operation requires a constant daily light integral, which can be achieved only through shading or supplemental lighting, as required (a short review of supplementary light control may be found in Albright *et al.*, 2000). Deviations from the optimal constant daily light are penalised by insufficient head size if light is deficient, and by leaf tip burn (LTB) blemishes if light is excessive. Since the potential losses of yield from insufficient lighting (in winter) and from LTB damage, due to excessive light (in summer) are

Notation

Note: PAP is acronym for photosynthetically active photons

C	annual cost of rent for lighting equipment, $\$\,\mathrm{m}^{-2}$ [ground] yr^{-1}
c	number of cohorts (daily harvests) in 1 yr
D	daily light-integral target, mol[PAP] m^{-2} [ground] d^{-1}
d	number of control decisions per unit time, h^{-1}
g	proportionality factor for rent of lighting equipment, $\$\,\mathrm{h}\,\mathrm{mol}^{-1}$[PAP] yr^{-1}
I	light integral, mol[PAP] m^{-2}[ground]
i	light flux, mol[PAP] m^{-2}[ground] h^{-1}
J	annual performance criterion, $\$\,\mathrm{m}^{-2}$[ground] yr^{-1}
j	instantaneous (hourly) performance criterion, $\$\,\mathrm{m}^{-2}$[ground] h^{-1}
K	annual cost of electricity, $\$\,\mathrm{m}^{-2}$[ground] yr^{-1}
k	number of non-overlapping intervals with surplus light for cohort n
L	leaf tip burn (LTB) characteristic time, d
l	day of residence (age) for cohort q
m	counter of surplus light occurrences
p	price of lettuce head, $\$\,\mathrm{head}^{-1}$
q	cohort number
T	residence time in greenhouse, d
t	time, h
V	annual value of crop, $\$\,\mathrm{m}^{-2}$[ground] yr^{-1}
y	surplus light-integral deviation, mol[PAP] m^{-2}[ground]
z	deficit light-integral deviation, mol[PAP] m^{-2}[ground]
η	saleable fraction of harvest
θ	time of day, h
λ	incentive (penalty) coefficient, $\$\,\mathrm{mol}^{-1}$[PAP]
v	number of lettuce heads planted (harvested) per day, head m^{-2}[ground] d^{-1}
π	unit price of light, $\$\,\mathrm{mol}^{-1}$[PAP]
ρ	$(=1,2,3)$ type of daily light trajectory
σ	light transmissivity of shade
τ	light transmissivity of greenhouse cover

Subscripts

1,2	specific light-integral deviations
a	installed artificial light
b	beginning of susceptibility period
C	current control strategy
e	end of susceptibility period
f	off-peak electricity
fn	switching from off-peak to on-peak electricity
max	maximum surplus light deviation
min	maximum deficit light deviation
N	new control strategy
n	on-peak electricity
nf	switching from on-peak to off-peak electricity
o	outdoor light
R	reference control strategy
r	reference
s	shade
δ	deficient light
σ	surplus light

Superscripts

*	corrected daily light integral
D	daily
L	lighting on
L	leaf tip burn (LTB) characteristic time
l	day of residence for cohort q
N	no control
q	cohort counter
S	shading on
T	residence time

high, a rather tight light control is required, which has been successfully achieved by means of a rule-based light control strategy (Albright *et al.*, 2000).

The LTB disorder (Frantz *et al.*, 2004), to which some lettuce cultivars are more susceptible than others, is thought to be the result of calcium deficiency at the growing tips, similar to the blossom end rot (BER) disorder in fruits (Marcelis & Ho, 1999; Tabatabaei *et al.*, 2004). The disorder apparently manifests itself when the growth rate exceeds the supply rate of calcium for a period of time over which the buffer of available calcium is exhausted. The most straight-forward means of preventing LTB is to reduce growth rate by restricting light to a level that for the Cornell conditions (Both *et al.*, 1998), is 16–17 mol[PAP] m^{-2}[floor] d^{-1} (where PAP is the acronym for photosynthetically active photons).

The current control algorithm attempts to achieve a constant light integral every day of the year. Recognising, however, the existence of some Ca buffering capacity, the requirement of a constant daily integral may be relaxed and replaced by a constant moving integral over a characteristic time, found by experience to be about 3 days. The control algorithm has been developed intuitively by trial and error and fitted to local conditions. Its main features are that (1) it makes and utilises an hourly projection (forecast) of the light integral to the end of the day, (2) it expects that the off-peak (less expensive) electricity is at the later part of the night, (3) its performance criterion (objective function) considers explicitly only the cost of supplementary light (implying a very steep penalty for any deviation from the 3-day light integral target), and (4) it is calibrated separately for different seasons.

The objective of this paper is to develop and test a simpler, more general control strategy, which may be easier to modify when conditions change. In particular, the suggested strategy, which reacts to deviations from a reference light trajectory, (1) does not require light projections, (2) makes no assumptions about the timing of off-peak electricity prices, and (3) is calibrated in conjunction with an explicit economic performance criterion. Up till now, only joint calibrations for all months have been attempted.

The already operational rule-based control strategy is referred to as strategy C (current) and the new strategy is referred to as strategy N (new). Both are compared with a reference strategy R, which is based on the assumption that a perfect forecast of the outdoor daily light integral (solar radiation) is available. None of these is a truly optimal strategy.

This paper summarises a simulation study where the two 'competing' strategies C and N, as well as the reference strategy R, are used to produce annual control trajectories for supplementary-light and shading, at several US geographic locations. The various control trajectories are then evaluated in conjunction with the same criterion, for comparison of their expected economic performance. It is assumed that the criterion is exact and that all plants of the same age are identical. Finally, the better-performing strategy N is used to demonstrate (1) the sizing of control equipment, and (2) its performance when the installed capacity is infra-optimal.

2. Control strategies and simulations

2.1. *Strategy C (current)*

The rules to achieve a pre-specified daily light integral are described in detail in Albright *et al.* (2000). Therefore, only a brief description is offered here. There are altogether eight rules for supplementary light control and two for shading control. The first light-control rule deals with the need to turn off the lights during certain hours of the day (not relevant to this study). The second postpones lighting as much as possible during the brighter part of the year. The third prevents surplus lighting any time. The next three rules postpone lighting to the off-peak period, and the last rule prevents insufficient lighting during the darker part of the year. The first shading rule utilises the actual light over the last hour, and the second utilises all light accumulated since sunrise, to estimate the light expected until sunset and to shade accordingly. This strategy has been later modified for cases where a 3-day light integral (rather than a single-day integral) is considered more appropriate to maintain. For instance, if over the past 2 days a light integral deficit z has occurred, z (but no more than $5\,\mathrm{mol[PAP]\,m^{-2}}$) is added to the current day's target. The very significant gain achieved with this modification is illustrated in Seginer *et al.* (2005).

2.2. *Strategy N (new)*

Strategy N attempts to prevent costly deviations of the actual light integral from a reference light integral, by criterion-guided tracking. The simplest reference light trajectory is a constant flux, which over a period of 24 h accumulates the required daily light integral D in $\mathrm{mol[PAP]\,m^{-2}[ground]\,d^{-1}}$. Periodic references, more similar to natural light (*e.g.* no light at night), are expected to produce better results.

The reference integral is given by

$$I_r = \int i_r\{\theta\}\,\mathrm{d}t \tag{1}$$

where: $i_r\{\theta\}$ in $\mathrm{mol[PAP]\,m^{-2}[ground]\,h^{-1}}$ is the instantaneous reference light flux, at time of day θ in h; t is time in h; and I_r is the reference light integral in $\mathrm{mol[PAP]\,m^{-2}[ground]}$. The surplus deviation of the actual light integral I from the reference integral is

$$y \equiv I - I_r \tag{2}$$

A control rule that drives the actual trajectory towards the reference trajectory, may be based on an incentive (or penalty) to add (or remove) light, which depends on the deviation y (similar to integral control). The smaller (or more negative) the deviation, the higher is the incentive to adding light, and *vice versa*. Given an incentive function $\lambda\{y\}$ in $\$\,\mathrm{mol^{-1}[PAP]}$, such as in *Fig. 1*, the following is a plausible instantaneous performance criterion:

$$j = \lambda\{y\}(i - i_r\{\theta\}) - \pi\{\theta\}i_a \tag{3}$$

where: j in $\$\,\mathrm{m^{-2}[ground]\,h^{-1}}$ is the instantaneous criterion, i is the total actual light flux in the greenhouse (natural plus artificial minus shade), i_a is the artificial light flux, and $\pi\{\theta\}$ in $\$\,\mathrm{mol^{-1}[PAP]}$ is the unit cost of this light, which depends on the cost of electricity as a function of the time of day. The first term of Eqn (3) may be regarded as the added value from increasing the

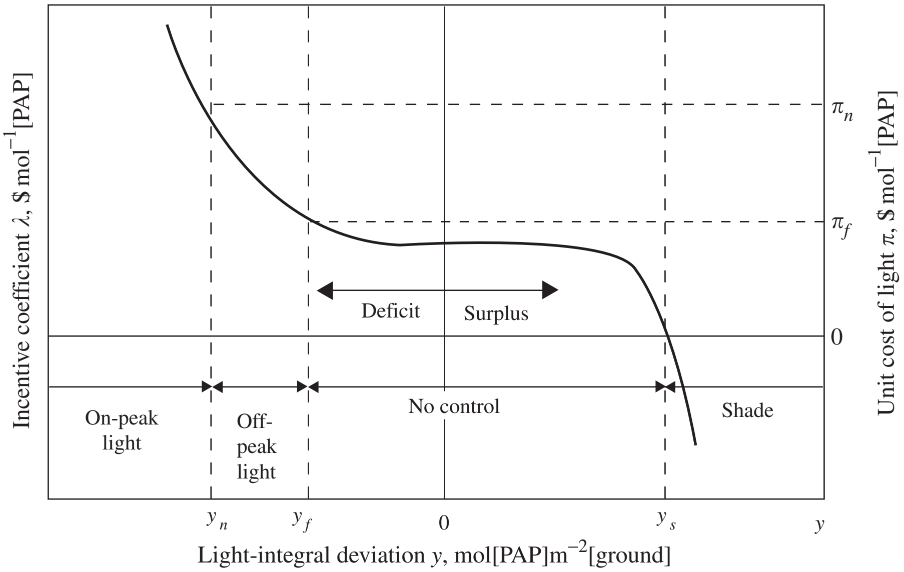

Fig. 1. A schematic incentive (penalty) function for the addition of light; the more negative the light deviation, y (light deficit), the larger the incentive for adding light; the deviations indicated by y_n and y_f are where, as the deviation increases (becomes less negative), light at 'on-peak' prices, and then at 'off-peak' prices is no longer justified; when the deviation reaches y_s, shading becomes justified

light deviation, while the second term is the associated cost. No cost is attached to shading.

In our case, only three control decisions are feasible: N—no control, S—shading, and L—lighting. Based on Eqn (3), the criterion values for these three decisions are

$$j^{\mathrm{N}} = \lambda\{y\}(\tau i_o - i_r) \tag{4}$$

$$j^{\mathrm{S}} = \lambda\{y\}(\sigma\tau i_o - i_r) \tag{5}$$

$$j^{\mathrm{L}} = \lambda\{y\}(\tau i_o + i_a - i_r) - \pi\{\theta\} i_a \tag{6}$$

where: τ (dimensionless) is the transmissivity of the cover to the outdoor light i_o; and σ is the transmissivity of the shading material.

The two boundaries between the three choices

$$j^{\mathrm{S}} - j^{\mathrm{N}} = \lambda\{y\}(\sigma - 1)\tau i_o = 0 \tag{7}$$

and

$$j^{\mathrm{L}} - j^{\mathrm{N}} = \lambda\{y\} i_a - \pi\{\theta\} i_a = (\lambda\{y\} - \pi\{\theta\}) i_a = 0 \tag{8}$$

define the switching values of y. The switching between shading and no-shading is when $\lambda\{y_s\} = 0$ [Eqn (7)], and the switching between lighting and no-lighting is at $\lambda\{y_f\} = \pi_f$ for the off-peak lighting and at $\lambda\{y_n\} = \pi_n$ for the on-peak lighting [Eqn (8)]. Hence, the incentive function $\lambda\{y\}$ is equivalent to the three switching values y_s, y_f and y_n, where $y_s > y_f > y_n$.

The resulting control rules are:

if $y_s < y$ (light surplus)	then shade
if $y_f < y < y_s$ (mild surplus or deficit)	then do nothing
if $y_n < y < y_f$ (light deficit)	then turn on light only if in the off-peak period
if $y < y_n$ (severe light deficit)	then turn on light even if in the on-peak period

It is intuitively clear that the narrower the range y_s to y_n, the smaller the resulting deviations from the reference integral I_r. While decreasing the deviations results, in general, in a smaller loss of yield, it may result in a higher cost (due, for instance, to shading and lighting on the same day).

2.3. *Strategy R (reference)*

This is a rather simple strategy, which aims at providing exactly the daily target light integral D on the assumption that a perfect forecast of the total daily natural-light (solar radiation) is available one day in advance. Suppose that the available natural light provides τI_o^D inside the greenhouse on a specific day; then the deficit (or surplus)

$$z^D = D - \tau I_o^D \tag{9}$$

can be used to calculate the most economical lighting (or shading) sequence for the day, which results in *exactly* the target light integral (provided that i_a is sufficiently large and σ is sufficiently small). In particular, if z^D is larger than can be supplied during the off-peak hours, the minimum on-peak lighting necessary to complete the daily target can be calculated.

Despite the perfect single-day optimisation, and the assurance of maximum yield, strategy R is not a truly optimal strategy. The reason is that, unlike the crop, it does not take advantage of the day-to-day light fluctuations. This point will be considered again below.

2.4. *Annual performance criterion*

The annual performance criterion J in \$ m^{-2}[ground] yr^{-1} is defined here as the difference between the revenue from selling the lettuce V on the one hand, and the costs associated with renting the space (or cost of ownership), with installing the lighting system C, and with operating it K, on the other hand. It is convenient to lump within the cost of rent also all constant *operational* expenses, such as labour and heating, and omit it altogether from the criterion, which covers a fixed period of time (1 yr). Hence

$$J = V - C - K = pv \sum_{q=1}^{q=c} \eta_\delta^q \eta_\sigma^q - g i_\alpha - i_\alpha \sum_{q=1}^{q=c} (t_f^q \pi_f + t_n^q \pi_n) \qquad (10)$$

where: c is the number of daily harvests (cohorts; $c = 365$ for the year), counted with q; p in \$ head^{-1} is the price (here constant) of one lettuce head; v is the number of lettuces planted and harvested each day; η_δ^q and η_σ^q are the saleable fractions, for cohort q, taking account of production losses due to periods of deficient and surplus light, respectively; g in \$ h mol^{-1}[PAP] yr^{-1} is the cost associated with installing one unit of light flux; and t_n^q in h and t_f^q are the durations of on-peak and off-peak supplemental lighting on day q. Note that the net income to the grower is considerably smaller than J, so that only *differences* between J's are of interest. Note also that the criterion may be applied to periods different than 1 yr.

For each control trajectory produced by any one of the three strategies C, N and R, the calculation of K and C is straightforward. The calculation of η_δ^q and η_σ^q, on the other hand, is based on rather crude estimates of the response of lettuce to deviations from the target light integral. Each cohort of plants is exposed to a somewhat different light history over its residence time T in d in the greenhouse. The effect of a too small light integral is that the heads do not reach the desired size, and when the loss of mass is significant, must be sold two for the price of one, leading to a value for η_δ^q of 0·5 for a deficit

$$z^T = TD - I^T \qquad (11)$$

greater than a certain value z_1 in mol[PAP] m^{-2}[ground]. If the deficiency is extreme, even two heads of lettuce may not sell for the price of one and they become valueless. Hence, if $z^T < z_2$, η_δ^q is set to zero.

Note that with this formulation, the daily light target can be reduced to

$$D^* = D - z_1/T \qquad (12)$$

without loss of production. In the computations with strategy R, this modified value of D has been applied explicitly.

If light is in excess of the target for L consecutive days (namely LD), and the plants are at a susceptible age, between ages l_b and l_e in days, LTB is likely to appear. The surplus light over the L days preceding day l is

$$y^L \equiv I^L - LD \qquad (13)$$

From experience, the saleable fraction of the produce may be approximated by

$$\begin{array}{llll} \text{if } 0 \leqslant y^L < y_1 & \text{then} & \eta_\sigma^l = 1 & \text{no damage} \\ \text{if } y_1 \leqslant y^L < y_2 & \text{then} & \eta_\sigma^l = \dfrac{y_2 - y^L}{y_2 - y_1} & \text{proportional damage} \\ \text{if } y_2 \leqslant y^L < \infty & \text{then} & \eta_\sigma^l = 0 & \text{total loss} \end{array} \qquad (14)$$

If, within the susceptible age, there are k non-overlapping intervals of length L for which $y^L > y_1$, then

$$\eta_\sigma^q = \prod_{m=1}^{m=k} \eta_\sigma^m \qquad (15)$$

Considering the two types of losses, from deficiency and from surplus of light, and noting that they are not mutually exclusive (two different mechanisms and time scales), the combined effect for a given harvest is obtained by the product $\eta_\delta^q \eta_\sigma^q$, as indicated in Eqn (10). Note that η_δ^q and η_σ^q may be modified to include penalty for not supplying the promised produce on time.

2.5. *Simulation*

The simulation study required two types of data: (1) values of the various parameters of the model, and (2) hourly solar radiation data for the location of interest. The standard parameter values, shown in the Appendix are based on the conditions prevailing at Ithaca, NY. Hourly solar radiation data of several US cities, distributed over a range of climates, has been used. The locations are Seattle (47°N), Ithaca (43°N), Chicago (42°N), Los Angeles (34°N), Tucson (32°N), Houston

(30°N) and Miami (26°N). For all of these the 1990 data were available. For Ithaca, data for 7 years, 1987–1993, were available.

Light control sequences (hourly lighting and shading decisions) were generated for periods of 1 year with the three control strategies, C, N (several variants) and R. These sequences were used as input to the evaluation of the annual performance criteria. Strategy N has several parameters that can be changed to improve its performance. First, an effective daily reference light trajectory needs to be selected. Three intuitively defined trajectories were used, all adding up to D: $\rho = 1$ refers to a uniform 24 h light flux, $\rho = 2$ refers to a sinusoidal daytime-light between 06:00 and 18:00 and zero light at night throughout the year, and $\rho = 3$ refers to a sinusoidal light between astronomic sunrise and sunset (longer days and lower noon-maxima in summer). Next, the number of control decisions per hour d may be selected, and finally, a search, for each case, over the three switching parameters y_s, y_f and y_n is used to calibrate strategy N.

3. Results and discussion

3.1. *Reference light trajectory*

Table 1 shows the effect of the reference light trajectory (column 2) and of the number of control decisions per hour (column 3) on the performance of strategy N. It also compares strategy N with the other two strategies, C and R. Note that, in view of Eqn (12), the daily light target for strategy R has been reduced to $D^* = 15{\cdot}6\,\mathrm{mol[PAP]\,m^{-2}\,d^{-1}}$, which results in some saving of electricity cost, without loss of saleable produce.

The table shows the following: (1) Judging by the criterion (column 11), reference light 2 ($\rho = 2$) is considerably better than 1. The gain by moving to reference 3 is marginal. (2) There is not much gain by increasing the decision rate d beyond $2\,\mathrm{h^{-1}}$. (3) The best values of the switching parameters y_s, y_f and y_n (columns 4–6) depend strongly on the choice of the reference light trajectory, but not much on d. The same findings also apply to Miami (not shown), where the solar climate is quite different from that of Ithaca. As a result, $\rho = 2$ and $d = 2$ have been selected for all later simulations.

Referring now to the three grey-highlighted rows of Table 1, strategy N is seen to perform considerably better than strategy C, and only slightly worse than strategy R. Strategy N is better than strategy C in terms of both loss of yield (from surplus light η_σ) and electricity requirement K (column 10). Table 1 shows no loss of production due to deficient light $\left(\sum_1^c \eta_\delta = 365\right.$ always; column 7$\left.\right)$, while occasionally there is some production loss due to surplus light (column 8). Correction of surplus light is more difficult than correction of light deficit, for at least two reasons: (1) Light deficit can be compensated for over the whole residence time T (here 24 days), while light surplus must

Table 1

Comparison of three control strategies, R—reference, C—current, and several variations of N—new, for Ithaca, NY (1990); y_n/D, y_f/D and y_s/D are the light deviations y (switching parameters), normalised with respect to the daily light target D, where on-peak light, off-peak light and shade, respectively, are turned off and on; $\Sigma\eta_d$ and $\Sigma\eta_s$ are total saleable harvests in 1 yr, due to deficient and surplus light, respectively; 'na' indicates not applicable; highlighted rows are selected for comparison among the strategies

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
Control strategy	*Reference light (ρ)*	*Decision rate (d), h^{-1}*	*Best $y_n/D,d$*	*Best $y_f/D,d$*	*Best $y_s/D,d$*	*No. of harvests*		*Value of crop (V), \$ $m^{-2}\,yr^{-1}$*	*Cost of light (K), \$ $m^{-2}\,yr^{-1}$*	*Criterion (J),\$ $m^{-2}\,yr^{-1}$*
						$\Sigma\eta_\delta$	$\Sigma\eta_\sigma$			
R	na	na	na	na	na	365·0	365·0	408·4	32·7	362·2
C	na	na	na	na	na	365·0	361·7	404·7	36·7	354·4
N	1	1	−0·32	−0·12	0·13	365·0	363·6	406·8	39·1	354·2
N	1	2	−0·32	−0·12	0·13	365·0	365·0	408·3	40·1	354·8
N	1	4	−0·37	−0·12	0·13	365·0	365·0	408·4	39·7	355·2
N	2	1	−0·63	−0·08	0·03	365·0	361·2	404·1	33·2	357·4
N	2	2	−0·61	−0·07	0·03	365·0	365·0	408·4	33·3	361·6
N	2	4	−0·61	−0·09	0·03	365·0	365·0	408·4	33·1	361·8
N	3	1	−0·61	−0·07	0·02	365·0	364·9	408·3	33·7	361·1
N	3	2	−0·64	−0·07	0·02	365·0	365·0	408·4	33·3	361·6
N	3	4	−0·63	−0·10	0·02	365·0	364·9	408·3	33·3	361·5

be compensated for within just L (here 3 days). (2) Artificial light can be added 24 h a day, if necessary, while shading is only effective during the light hours.

Note, again, that while the differences in the criterion seem small *relative* to the criterion itself, the *absolute* loss is what counts, since the net income is an order of magnitude smaller than the criterion.

3.2. *Robustness across years*

For a control strategy to be useful, its parameters (here the switching parameters y_s, y_f and y_n) should be invariable among years. Parameters derived from historical data should be suitable for future use. To check on the robustness among years, seven consecutive years at Ithaca were analysed, and the results summarised in Table 2. First, strategy N was calibrated for each year separately ('best'). The switching parameters were then averaged over all years and the calculations repeated with the averaged parameters ('common'). Finally, the two results of strategy N were compared with the results of strategies R and C.

Referring first to the individually calibrated years ('best', columns 1–8), the largest variation among years is in terms of the cost of light (column 7), this being the direct result of the variation, among years, of the natural light. No production loss due to light deficit, but some loss due to light surplus, are evident (columns 4 and 5). The variation of each of the 'best' switching parameters (columns 1–3) is within the calibration tolerance (0·01). The performance of strategy N with 'common' parameters is, on average, only slightly (0·6 \$ m^{-2} yr^{-1}) worse than the 'best' results (columns 8 and 9), but still considerably better than that of strategy C (column 11). These results show that parameter values based on historical data can be usefully applied to future years.

3.3. *Comparison among locations*

The next test for robustness is among locations. This is less critical than robustness among years, but would be convenient if the technology is to be transferred between climates. *Figure 2* compares the performance of the three control strategies, C, N and R, for seven US cities with different climates. There is a clear correspondence between the geographical latitude and the reference criterion J_R, as the order of cities along the abscissa shows. In general, the higher the latitude, the lower the criterion, losing more than 30 \$ m^{-2} yr^{-1} in cost of artificial light between the most southern and most northern location (assuming the same set of prices and ignoring differences in heating expenses).

While the cost (use) of lighting is approximately the same for all three control strategies (sloping line and squares), the productivity (diamonds) of strategy N is considerably better than that of strategy C, particularly

Table 2

Performance of several control strategies over several years in Ithaca, NY; R—reference strategy, C—current strategy, and N—new strategy; strategy N was employed in conjunction with reference light trajectory $\rho = 2$ (6–18 sinus light) and decision rate $d = 2\,h^{-1}$; y_n/D, y_f/D and y_s/D are the light deviations y (switching parameters), normalised with respect to the daily light target D, where on-peak light, off-peak light and shade, respectively, are turned off and on; $\Sigma\eta_d$ and $\Sigma\eta_s$ are total saleable harvests in 1 yr, due to deficient and surplus light, respectively; 'best' indicates best switching parameters for particular year; 'common' indicates that means over all seven values of a switching parameter have been used for all years; 'SD' indicates standard deviation

	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*
Year	*Best y_n/D, d*	*Best $y_f/$ D,d*	*Best y_s/D, d*	*No. of harvests*		*Value of crop (V), \$ m^{-2} yr^{-1}*	*Cost of light (K), \$ m^{-2} yr^{-1}*	*Criterion(J_N), \$ m^{-2} yr^{-1}*	*Criterion (J_N), \$ m^{-2} yr^{-1}*	*Criterion (J_R), \$ m^{-2} yr^{-1}*	*Criterion (J_C), \$ m^{-2} yr^{-1}*
				$\Sigma\eta_\delta$	$\Sigma\eta_\sigma$						
	Strategy and comment										
	N best	*N best*	*N best*	*N best*	*N best*	*N best*	*N best*	*N best*	*N common*	*R*	*C*
1987	−0·62	−0·07	0·02	365·0	364·7	408·1	31·1	363·5	362·1	364·8	352·1
1988	−0·62	−0·07	0·02	365·0	365·0	408·4	28·4	366·5	365·9	367·2	357·1
1989	−0·63	−0·05	0·02	365·0	365·0	408·4	32·0	362·9	362·9	363·6	353·6
1990	−0·62	−0·07	0·02	365·0	365·0	408·4	33·3	361·6	361·4	362·2	354·4
1991	−0·64	−0·07	0·01	365·0	365·0	408·4	29·9	365·0	364·5	365·5	350·4
1992	−0·64	−0·04	0·01	365·0	363·7	407·0	36·1	357·4	356·2	359·5	344·6
1993	−0·65	−0·04	0·01	365·0	365·0	408·4	32·8	362·1	361·5	363·0	353·4
Mean	−0·63	−0·06	0·02	365·0	364·8	408·2	31·9	362·7	362·1	363·7	352·2
SD	0·01	0·01	0·01	0·00	0·47	0·53	2·49	2·89	3·06	2·49	3·95

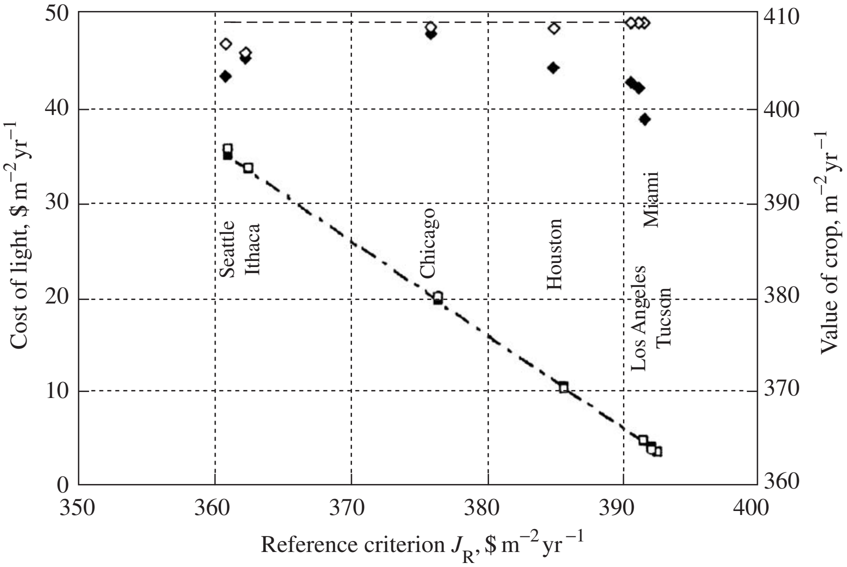

Fig. 2. Performance of the control strategies C—current, N—new and R—reference, over a range of climates; the normalised switching parameters of strategy N, common to all locations, are $y_n/D_r = -0{\cdot}61$ d, $y_s/Dr = -0{\cdot}09$ d and $y_f/D_r = 0{\cdot}05$ d, where the light deviations y are normalised with respect to the reference daily light target D_r; the subscripts n, s, and f, indicate on-peak light, off-peak light and shade, respectively. Cost of light: ■, strategy C; □, strategy N; —·—, strategy R. Value of crop: ◆, strategy C; ◇ strategy N; — —, strategy R

at the lower latitudes. The productivity of strategy N at the lower latitudes is in fact even marginally better than that of the reference strategy, R. The latter observation can be explained by the fact that strategy N takes advantage of the (among days) buffering capabilities of the crop, while strategy R optimises for each day separately.

The results of strategy N are all for the same set of switching parameters y_n, y_f and y_s. This resulted in only slightly smaller criteria than for location-specific parameters (378·9 $ m^{-2} yr^{-1} on average instead of 379·7 $ m^{-2} yr^{-1}). The conclusion is, therefore, that the parameter values are not only insensitive to the year-to-year variations, but also to significant changes of latitude. This is also true for strategy C.

3.4. *Sizing of control equipment*

Any one of the control strategies can be used to find the optimal size of the control equipment for a given set of conditions, by searching in the light i_a and shade σ control space. To do that, the performance criterion J should include the cost of renting the control equipment (or repaying the loan). The cost of the lighting system was assumed to be proportional to the installed flux (or number of luminaires; Eqn (10)). The transmissivity of the shading material has a marginal effect on the cost of the shading system, which therefore was assumed not to change with transmissivity.

Figure 3 shows the results of sizing with strategy N, for the same seven locations as before. The ordinates are *differences* between the results obtained with the best equipment size for each location and the results for identical (‘standard’) equipment at all locations. While intuitively one might expect the optimal lighting capacity and transmissivity to increase with latitude (right to left), the results show that the highest recommended values of i_a and σ are at the middle latitudes. Since these happen to be closer to the common standard values ($i_a = 0{\cdot}9$ mol m^{-2} h^{-1}; $\sigma = 0{\cdot}4$), the deviation of the criterion in the middle range is minimal. The differences between locations, in terms of equipment size and performance criterion, while not negligible (2·7 $ m^{-2} yr^{-1} in Tucson), are also not large, justifying perhaps the same design for the whole climatic range (possibly intermediate values, such as $i_a = 0{\cdot}8$ mol m^{-2} h^{-1} and $\sigma = 0{\cdot}35$ are best; not checked). Note, however, that the results are based on just 1 yr of solar radiation data at each location.

3.5. *Operation with undersized control equipment*

Strategies R and N were used to explore their usefulness when the equipment is undersized (not enough supplementary light or shade). This required some modification of the control algorithm of N to prevent the accumulation of an unmanageable deviation (antireset-windup). For example, if the installed capacity

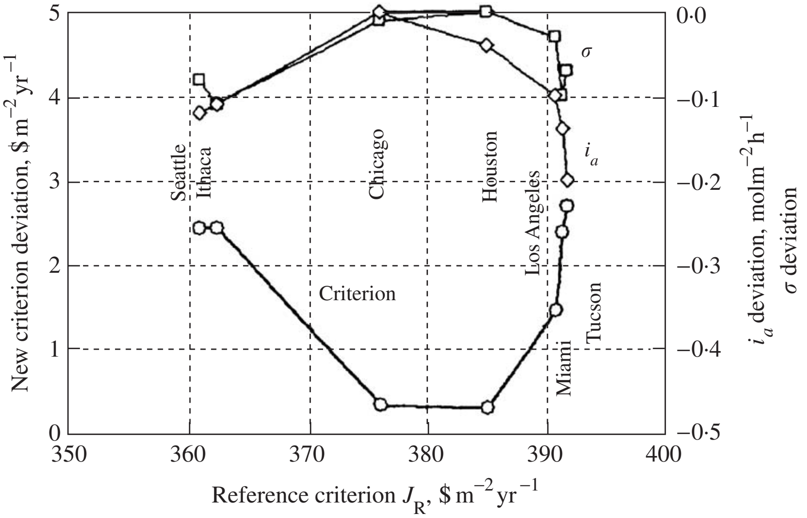

Fig. 3. Differences between size of control equipment and performance criterion of systems sized according to local conditions and systems of a standard size ($i_a = 0{\cdot}9\,mol\,m^{-2}\,h^{-1}$; $\sigma = 0{\cdot}4$); the order of locations is the same as in Fig. 2; all deviations are 'best' minus 'standard'; □ shade transmissivity deviation (σ); ◇, lighting capacity deviation (i_a); ○, criterion deviation (J_N)

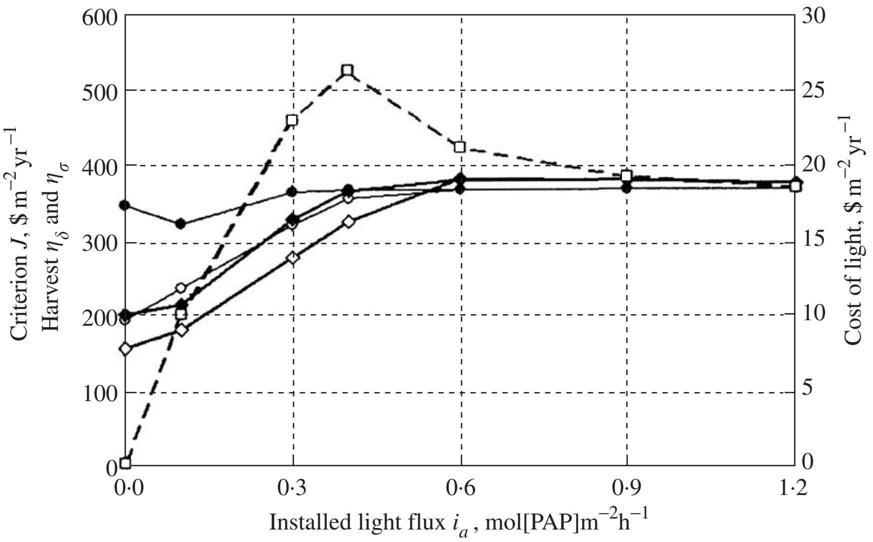

Fig. 4. Performance of greenhouse systems with insufficient lighting equipment, Chicago 1990; ○, saleable fraction due to light deficiency η_δ, strategy N (new); ●, saleable fraction due to light surplus η_σ, strategy N; ◆, performance criterion for strategy N (J_N); ◇, performance criterion for the reference strategy R (J_R); □, cost of electricity for light K, strategy N

of supplementary light is unable to drive the light integral back to the reference within a couple of days, a season-long negative deviation may accumulate which will later require a long 'wind-down' period before proper shading decisions can be made. To prevent this from happening, the calculated deviation is not permitted to over- and under-flow the boundaries y_{max} ($>y_s$) and y_{min} ($<y_n$). The two new parameters, y_{max} and y_{min}, together with y_s, y_f and y_n, must be adjusted during calibration (altogether a five-dimensional search). Figures 4 and 5 show the performance results for Chicago (1990), which was selected for its middle position in Figs 2 and 3.

Figure 4 shows that there is no advantage in installing a higher lighting capacity than 0·6 mol[PAP] m^{-2} h^{-1}. If the capacity drops below that value, however, loss of yield due to light deficiency η_δ becomes significant, resulting in a sharp decline of the economic performance

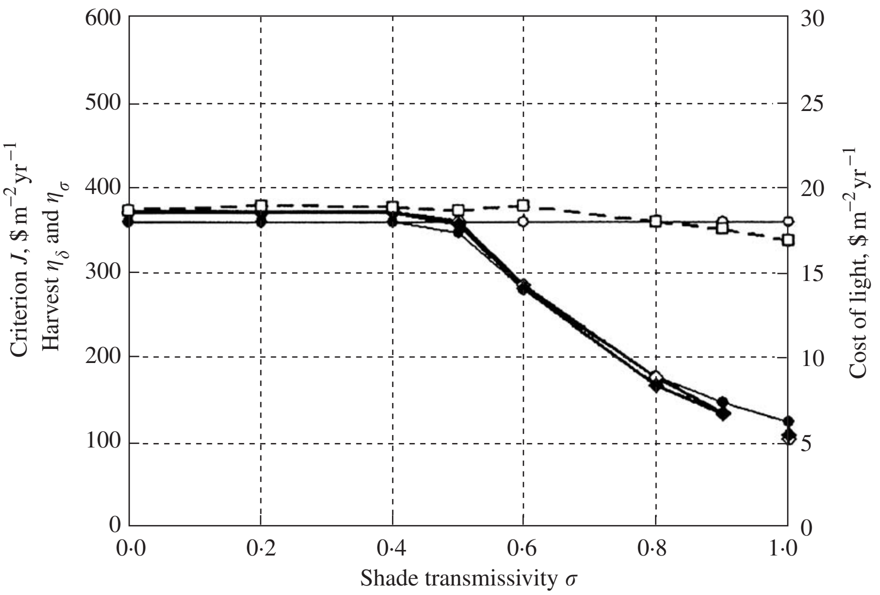

Fig. 5. Performance of greenhouse systems with insufficient shading, Chicago 1990; ○*, saleable fraction due to light deficiency* η_δ*, strategy N (new);*●*, saleable fraction due to light surplus* η_σ*, strategy N;*◆*, performance criterion for strategy N* (J_N)*;*◇*, performance criterion for the reference strategy R* (J_R)*;*□*, cost of electricity for light K, strategy N*

J_N. Note that one would expect more loss of yield in northern latitudes (compared to Chicago) and *vice versa*. The loss of yield due to surplus light η_σ is small. The peak in the cost of lighting at about $i_a = 0{\cdot}4\,\mathrm{mol\,m^{-2}\,h^{-1}}$ is due to increased utilisation of on-peak electricity, when off-peak lighting becomes insufficient.

A comparison, in *Fig. 4*, between the criteria of strategies N and R, shows that strategy N is doing considerably better than strategy R when the installed capacity is lacking. While strategy R manages to prevent any loss of yield due to surplus light (not shown), it loses a lot of yield due to light deficit (not shown). The reason is that it does not permit any surplus light on a particular day to be carried over to future days, where it may be needed to compensate for insufficient light. Strategy N manages this task considerably better, at the cost of some loss due to surplus light.

Figure 5 shows what happens when shading is insufficient. Beyond a shade transmissivity of about 0·4, the loss of yield due to light surplus becomes significant. *Figure 5* is simpler than *Fig. 4* in the following respects: (1) there is no loss due to light deficiency, (2) the expenditure on light is only slightly affected by the insufficient shading, and (3) the difference between the performance of strategies R and N is negligible. Note the gap in the criteria lines between the results for $\sigma = 0{\cdot}9$ and $\sigma = 1{\cdot}0$. The points for $\sigma = 1{\cdot}0$ should be higher by an amount that represents the cost of the deployment mechanism, no longer required when there is no shade.

The reason for the slight reduction in cost of light at high shade transmissivities [item (2) above], is probably that under normal conditions some light is used to compensate for inadvertent over-shading. When over-shading does not happen, there is no need for compensation. The similar performance of strategies R and N [item (3)], in contrast with the situation in *Fig. 4*, is probably due to the short response time of LTB to light surplus: even strategy N apparently cannot do much about it.

3.6. *Further remarks*

This study focuses on light control, assuming that lighting decisions are independent of other control decisions, such as temperature control. The main consequence of this is that direct economical comparisons between locations (*Figs 2* and *3*) are biased in favour of the northern latitudes, where heating expenses are higher. A more sophisticated optimization scheme should consider crop response to heating and CO_2 enrichment, as well as to light. Such a control also involves ventilation decisions which are strongly influenced by humidity considerations. In that general case a daily *growth* target should replace the daily *light* target. Since reasonably good lettuce growth models are available (van Henten, 1994; Seginer, 2003) this should be possible.

The new strategy N has been tested for robustness to differences among years and among locations (climates). It has also been used to size the control equipment and explore its performance when the installed capacity of the control equipment is insufficient. The strategy can be further tested by changing other parameters of the problem, such as (1) electricity and lettuce prices, (2) timing of off-peak electricity, (3) size of lettuce heads to be marketed and (4) different yield responses to surplus and deficient light. All four factors may change from one (annual) contract to the next. Robustness with respect to these factors means that a smooth transition from contract to contract should be possible (no need for re-calibration). The fourth factor, related to changing varieties, is the more difficult one to handle.

It may well be that some gain can be obtained by varying the reference light trajectory and the switching parameters between seasons within the year. Seasonal calibration has been successfully used in strategy C.

4. Conclusions

The new strategy N has been shown to perform considerably better than the current strategy C. Strategy N is on average almost as good as the reference strategy R (which requires daily light forecasts) and in certain cases (for instance when the installed lighting capacity is insufficient), it actually out-performs strategy R. Strategy N is easily adaptable to changes in climate, prices and any other parameters that enter the computer program explicitly. Note, however, that all three strategies are restricted to uniform production throughout the year.

All strategies are rather robust to change of conditions between years and among locations. Strategies C and R, in their current form, have no adjustable parameters, and the best parameters of strategy N change little among years and locations.

The results of this study show that the performance criterion contains information that is essential to the development of a successful control strategy. Starting from the simple requirement of a constant daily light integral, all three strategies evolved to consider at least some of the information contained in the performance criterion. Strategy C has been modified to replace the single day targets with 3-day targets, since this is the characteristic response time for leaf tip burn (LTB). Strategy R has been modified by slightly reducing the daily target in view of the permissible loss of production. Strategy N uses three adjustable switching parameters in a calibration process which considers the complete information contained in the performance criterion. This complete use of information, in an otherwise rather unsophisticated control scheme, is probably the reason for the success of strategy N. The importance of the performance criterion means, however, that its formulation needs to be as accurate as possible. At present, the criterion seems the least reliable element of any light control scheme, since it contains the uncertain crop responses to surplus and deficit light.

The success of the reference strategy R is due to the availability to it of a perfect daily radiation forecast. This, however, is not enough for a truly optimal strategy, which needs a forecasting horizon equal at least to the residence time of the plants in the greenhouse. While the daily forecast is obviously useful, the performance of strategy N is close enough to that of strategy R, so that expending much effort to improve the current forecasting situation seems not to be justified.

Given a performance criterion, the best sizes of the lighting and shading equipment can be determined by simulation with a range of sizes. It turns out that for the particular problem of uniform production throughout the year, the best size of the light control equipment is not sensitive to the range of solar radiation climates within the US (certainly *not* true for the heating equipment). Under-sized equipment leads to losses of yield far beyond the saving in installation costs. In general, for the set of prices considered here, the best outcomes are associated with close-to-perfect production of the target yield. In other words, the cost of control is low enough to justify a complete coverage of all needs.

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Appendix: Standard parameter values

Parameter	*Value*
Engineering parameters	
Transmissivity of cover to light τ	0·6
Shade transmissivity σ	0·4
Light flux of luminaries i_a, mol[PAP] m^{-2}[ground] h^{-1}	0·9
Switching time from off-peak to on-peak electricity θ_{fn}, h	07:00
Switching time from on-peak to off-peak electricity θ_{fn}, h	22:00
Horticultural parameters	
Time constant for leaf tip burn L, d	3
Residence time of cohort in greenhouse T, d	24
Production rate of lettuce heads v, head m^{-2}[ground] d^{-1}	1·67
First susceptible residence day l_b, d	12
Last susceptible residence day l_e, d	21
Prices	
Unit price of off-peak light π_f, \$ mol^{-1}[PAP]	0·0160
Unit price of on-peak light π_n, \$ mol^{-1}[PAP]	0·0252
Price of lettuce head p, \$ $head^{-1}$	0·67
Proportionality factor for rent of lighting equipment g, \$ h yr^{-1} mol^{-1}[PAP]	15
Light-integral and corresponding losses	
Reference daily light-integral D, mol[PAP] m^{-2} [ground] d^{-1}	16
Light-integral deficit beyond which marketable fraction is reduced to η_1 z_1, mol[PAP] m^{-2}	10
Light-integral deficit beyond which lettuce has no value z_2, mol[PAP]m^{-2}	100
Saleable fraction beyond y_1 η_1	0·5
Surplus L-day light-integral range of loss y_1, y_2, mol[PAP] m^{-2}	3,10

Note: PAP is photosynthetically active radiation.