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THE MODULATED UV–B IRRADIATION SYSTEM AT THE UNIVERSITY OF JOENSUU

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APHALO, P. J., TEGELBERG, R. and JULKUNEN–TIITTO, R. *The modulated UV–B irradiation system at the University of Joensuu.* BIOTRONICS **28**, 109–120, 1999. This note describes the modulated system for outdoor UV–B irradiation located at the botanical gardens of the University of Joensuu. The system was built from off–the–shelf parts and is controlled and monitored by a datalogger. A detailed description and results from some tests are presented.

Key words: datalogger as controller; modulated system; UV–B; ultraviolet–B radiation.

INTRODUCTION

The modulated system for outdoors UV–B irradiation located at the botanical gardens of the University of Joensuu was built during the spring and summer of 1997. This is the largest UV–B supplementation system in Finland, and by the number of replicate frames a large installation compared to several other European modulated systems (Fig. 1). The system was built for carrying out experiments on the effects of increased UV–B on herbivory in tree seedlings and saplings, as part of the project "Herbivory in relation to variable defences of woody plants" led by Prof. Jorma Tahvanainen.

A modulated irradiation system is a system in which the UV–B radiation increase tracks in real time the changes in solar UV–B. Solar UV–B is constantly monitored and the output from the lamps is very frequently adjusted to keep an almost constant *proportional* increase in UV–B —e.g. a constant increase of 50% of $UV\text{–}B_{BE}$.

Modulated systems are the best set–up currently available for studying responses of plants to increased UV–B under natural conditions (*3*). They have been in use for a couple of decades. The first systems had custom built controllers (*2*), but nowadays it is possible to build such a system from components available off–the–shelf.

As modulated systems are used outdoors, they should work well under a wide range of ambient conditions: air temperature is especially important for the functioning of fluorescent lamps. The system described here has a higher minimum working temperature (−5–0℃) than those with custom–made

Fig. 1 Partial view of the modulated UV–B supplementation system in Joensuu. Two years old birch seedlings growing under the frames.

controllers, but construction is easier and cheaper.

Increased UV–B experimental set–ups which use acetate–filtered lamps have usually included controls with polyester–filtered lamps. These two lamp–plus–filter combinations differ mainly in their UV–B emission, but both do emit a small quantity of UV–A. Recently, the need of additionally having a control with un-energized lamps has been stressed (*5*), and our system follows this recommendation.

The hardware, software and performance of the system are discussed in the respective sections below. The listing of the logger program is available at http://cc.joensuu.fi/photobio/mod_sys.html.

HARDWARE

The system comprises 21 aluminum frames, with six lamps each. Of these 21 frames, seven have un–energized lamps (sunlight controls), seven have lamps covered with polyester film (UV–A controls), and seven have lamps covered with cellulose diacetate film (increased UV–B treatment). The frames are laid out in the field grouped in seven blocks of three frames (Fig. 2).

Each frame, built from 25 mm square section tube is 1.5 m wide and 3.0 m long (Fig. 3). The frames are held on four 2.6 m tall poles made from 50 mm round section aluminum tube. Lamps in each frame are located following a "cosine" distribution (*1*) and are kept 0.60 m above the top of the plants. The area under the frames which is useful for growing experimental plants is approximately 0.80 m×2.40 m, with a variation in UV–B irradiance from the lamps of ±10%. Frames are 2.5 m apart in all directions.

The lamps used are special T12 40 W fluorescent tubes, 1.20 m long (UVB–

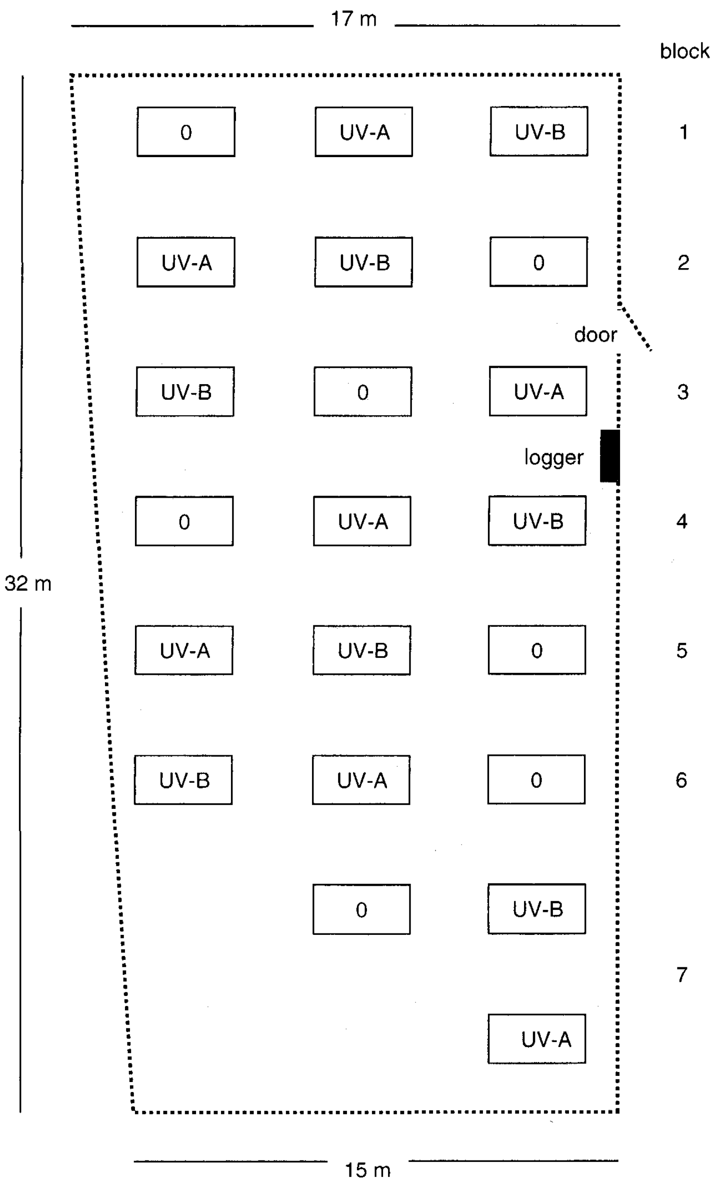

Fig. 2 Plan of the experimental field, showing location of frames, logger (and electrical switch-box) and fence. Allocation of treatments to frames for a particular experiment is shown: 0, sunlight control; UV-A, UV-A control; UV-B, elevated UV-B treatment.

313, Q-Panel Co., Cleveland, Ohio). The lamps are driven, in pairs, by high frequency dimming ballasts[1] (PC 2×32 A011, Tridonic Bauelemente GmbH, Dornbirn; Austria). These ballasts are controlled by a digital serial signal (DSI)

[1]The ballasts used are not the best for T12 40 W fluorescent tubes, and lamp lifespan is drastically reduced if dimmed down to the rated 1% of full output, however, they work satisfactorily if they are not dimmed below 3–4%. Start-up occurs at 10% of maximum output. Other ballast types from the same manufacturer may give better performance: PC 2×36 TCL A011 should allow dimming down to 1% without reduced lamp life, and PC 2×36 ↗

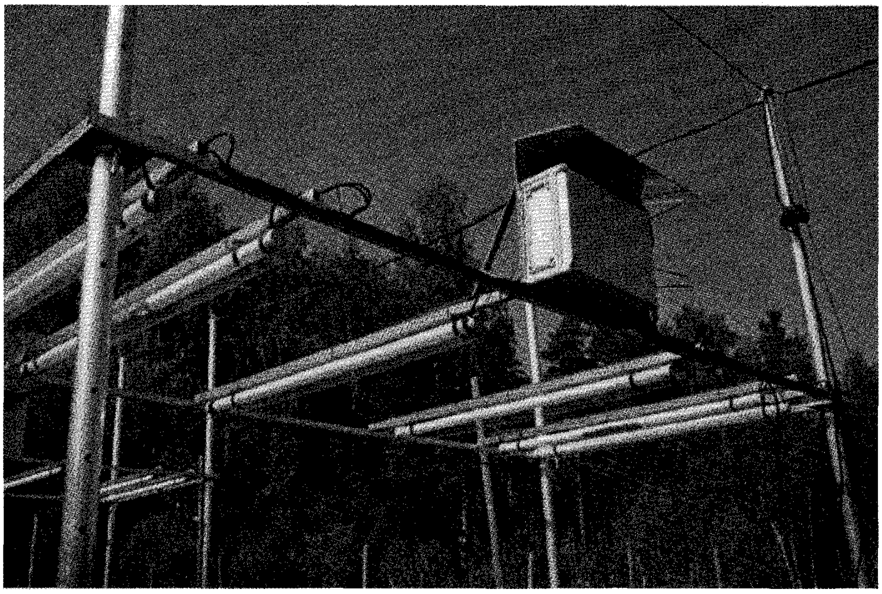

Fig. 3 Photograph of a lamp frame.

Table 1. Sensors.

Sensor	Variable measured	Manufacturer
BW-20	UV-B, CIE weighted	Vital Technologies, Bolton, Ontario, Canada.
LI-190-SA	PAR	Li-Cor, Lincoln, NE, USA.
50Y	Air temp. and RH	Vaisala Oy, Helsinki, Finland.
107	Soil temperature	Campbell Scientific Ltd., Shepshed, UK.

and so the signal is not affected by the length of the wires. The DSI signal is generated by an interface unit (DSI 004, Tridonic Bauelemente GmbH, Dornbirn, Austria) controlled by an analogue voltage signal (1 V to 10 V) for dimming between 1% and 100% of the maximum lamp output, and an on/off relay switch for remotely switching the lamps.

The sensors used are listed in Table 1. The two BW-20 UV-B sensors were selected by the manufactured for matched calibration constants. In spite of this they are matched only at 20℃. Over the range of 0℃ to 35℃ their sensitivity is also matched, but the change with temperature of the dark offset is very different. The temperature sensitivity of the calibration constants was measured under controlled conditions,[2] and the constants used are calculated, separately for

↘ Excel, allows start-up at 1% of maximum output. According to specifications ballasts from Philips and Osram have higher minimum temperatures for dimming. This was confirmed in our tests of Osram's Quicktronic dimmbar de luxe ballasts.

[2]The sensors and lamps were installed inside an environmental chamber (PGW36, Conviron, Winnipeg, Canada) and their output compared to each other and to measurements done with an spectroradiometer located outside the chamber, under constant ambient temperature of approx. 22℃, with only the light collector, connected with a fiber-optic light-guide, inside the chamber.

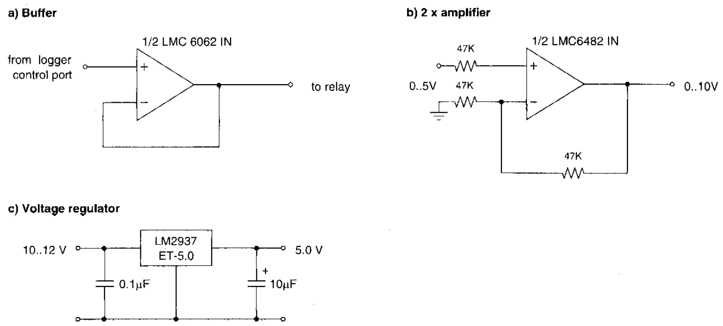

Fig. 4 Circuit diagrams of a) the current buffer and b) the amplifier used to interface the datalogger to the DSI interface adaptor driving the dimming ballasts, and c) the regulated power supply for the UV-B sensors. The operational amplifiers and the voltage regulator are powered from the logger battery. All integrated circuits are manufactured by National Semiconductor.

each sensor, in real time as a function of air temperature.

The controller used is a data-logger (CR10, Campbell Scientific Ltd., Shepshed, England), with an analogue output peripheral (SDM-AO4, Campbell Scientific). The program described in section 2 modulates the output of the lamps.

The custom-made electronics are extremely simple: an op-amp is used to buffer the output of one of the logger's control ports. The output of this op-amp controls a relay that switches the lamps on and off by means of the analogue to DSI interface adaptor. Another op-amp is used to amplify the 0 V to 5 V output of the logger peripheral to the voltage required by the DSI interface (see Fig. 4 for circuit diagrams). The logger, and all other electronic components, including ballasts, are rated to work from −25℃ to +50℃. However, the ballasts cannot dim the output of the lamps at air temperatures below approximately −5℃.

SOFTWARE

The "modulator" program runs on a Campbel CR10 (or CR10X) datalogger.[3] It is a differential system with a reference UV-B sensor under a control lamp canopy with lamps covered with polyester film, and a feed-back UV-B sensor located under a treatment lamp canopy with lamps covered with cellulose diacetate film. The system uses a feed-back loop to give a fractional increase in UV-B in the treatment compared to the control. A feed-back system like this is not dependent on the absolute calibration of the sensors, but just on the cross-calibration between the two sensors. Such a system is much less sensitive to effects of ambient temperature on the slope of the calibration than a system based on a single sensor. However, it is more sensitive to drift in the offset (the

[3]The listing of the program is available at http://cc.joensuu.fi/photobio/mod_sys.html.

output in darkness) which is also dependent on ambient temperature.[4]

The main program table is executed once each minute. It can be divided into three parts: (A) taking initial readings from all the sensors, (B) adjusting the output of the lamps to the target level, (C) logging the measured environmental values and also values used to monitor the performance of the system.

Part A includes calls to several subroutines. First a flag is checked to find out if this is the first pass through the program table, in which case several input locations (program variables) and the output port are initialized. Values are read from all sensors, but in the case of the UV–B sensors values may be read again later if it is needed to adjust the dimmer.

Part B checks several environmental variables and disables lamps if the operating conditions are not fulfilled: these include background PAR, background UV–B irradiance, and air temperature. The thresholds have hysteresis so as to minimise the number of times per day that the lamps are switched on and off because repeatedly switching the lamps may significantly shorten their life.

Part C outputs summary values of the measured variables and of the performance of the system. Hourly summaries (average, maximum, minimum, and histogram values) are stored in memory, raw data are discarded.

Ultraviolet–B irradiance is measured by taking four pairs of readings from the two sensors, and calculating the average of the four values from each of the sensors. This is done to reduce noise. The average readings are used to calculate the increase in UV–B irradiance below the increased UV–B frame compared to the UV–A control frame. Then a target value is calculated based on the UV–B irradiance under the control frame, and using this target value, the ratio between the actual UV–B irradiance under the increased UV–B frame and the target UV–B irradiance is estimated.

The output of the lamps is regulated by changing the voltage fed to the DSI interface. The program uses a feed–back loop to adjust this voltage. The response of the dimming ballasts to voltage is not linear, it is approximately exponential, so the best approach is to increase voltage linearly. A step size of 0.10 V is used, as this increase in voltage gives an increase in lamp output of less than 10%, together with a dead–band of ±5% for the achieved output. We also check for the cases of reaching both the maximum or minimum allowed voltages, and abort by either setting lamps to maximum power, or to minimum allowed power.

[4]The offset correction is calculated as a function of ambient temperature, using sensor temperature could further improve performance. When using a single sensor, it is possible to check the offset by switching off the lamps once every few minutes, but this could decrease lamp life.

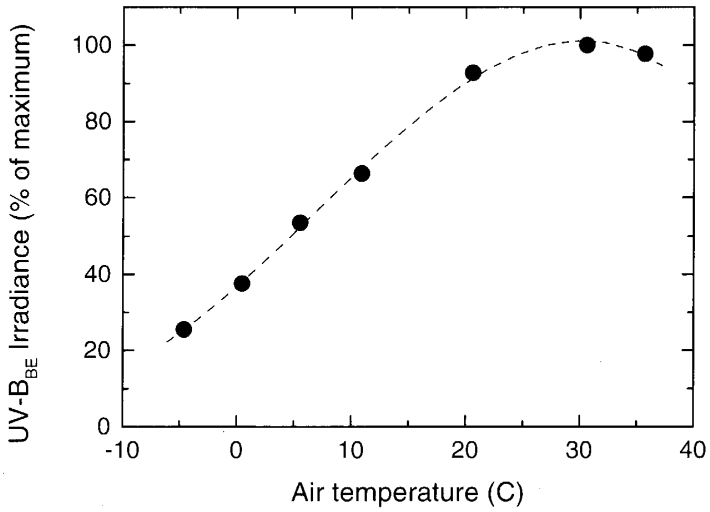

Fig. 5 Relative output of the cellulose–acetate filtered Q–Panel UVB–313 lamps as a function of air temperature. UV–B$_{BE}$ irradiance was measured with fibre optic light guide connected to a Macam SR–9010–PC spectroradiometer maintained at constant temperature of 22℃. Plot for irradiance at 313 nm is almost identical as the emission spectrum of the lamps was little affected by temperature.

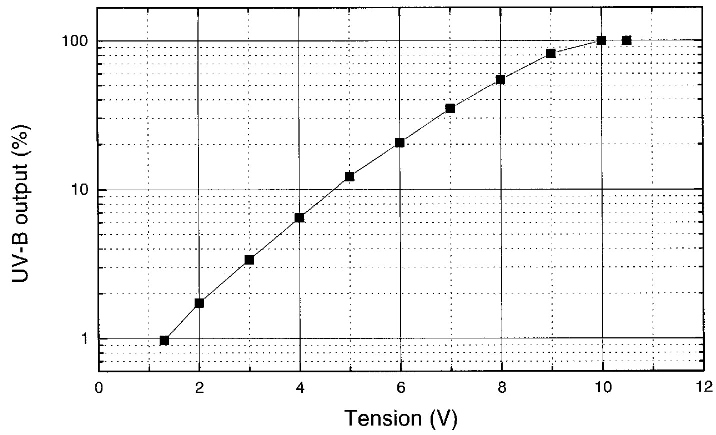

Fig. 6 Relative output of the Q–Panel UVB–313 lamps as a function of the voltage at the dimmer control input. UV–B irradiance was measured at 313 nm with a Macam SR–9010–PC spectroradiometer at 22℃.

TEST RESULTS

Performance of the lamps and ballasts

Fluorescent lamps (low pressure mercury lamps) are sensitive to ambient temperature. The actual drop in radiant output as temperature decreases depends both on lamp and on ballast characteristics. The maximum radiant output as a function of air temperature for the lamp plus ballast combination used in our system was measured in a controlled environment chamber (Fig. 5). In practice the lower UV–B output at low temperature is not a big problem

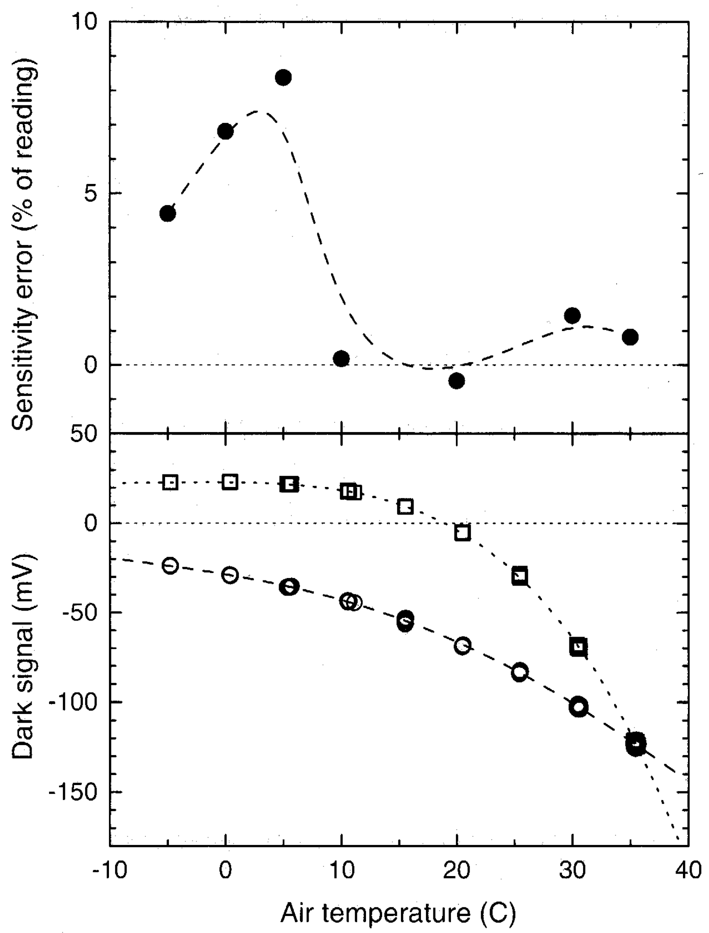

Fig. 7 Effect of ambient temperature on the performance of two Vital BW-20 ultraviolet sensors. (a) Relative sensitivity error (as difference in output between the two sensors after correction for dark signal), and (b) dark signal of the sensors (different simbol used for each sensor). Measured in an environmental chamber using Q-Panel UVB-313 lamps as a source.

because maximum natural UV-B irradiance occurs in the summer.

The radiant output of the lamps as a function of the control voltage (1 V to 10 V) applied at the input of the analogue to serial-digital signal converter was measured at one temperature (Fig. 6). The response is almost log-linear for the ballasts used.

Performance of the sensors

For a good performance of the system it is important that the calibration, and especially the cross-calibration of the sensors does not change with ambient temperature. If the calibration does change with temperature as is the case for the Vital BW-20 sensors used (Fig. 7), then the temperature dependence of calibration should be taken into account in real time in the control program. To prevent short-term fluctuations in their temperature the sensors were installed in aluminum 'jackets' to increase thermal mass.

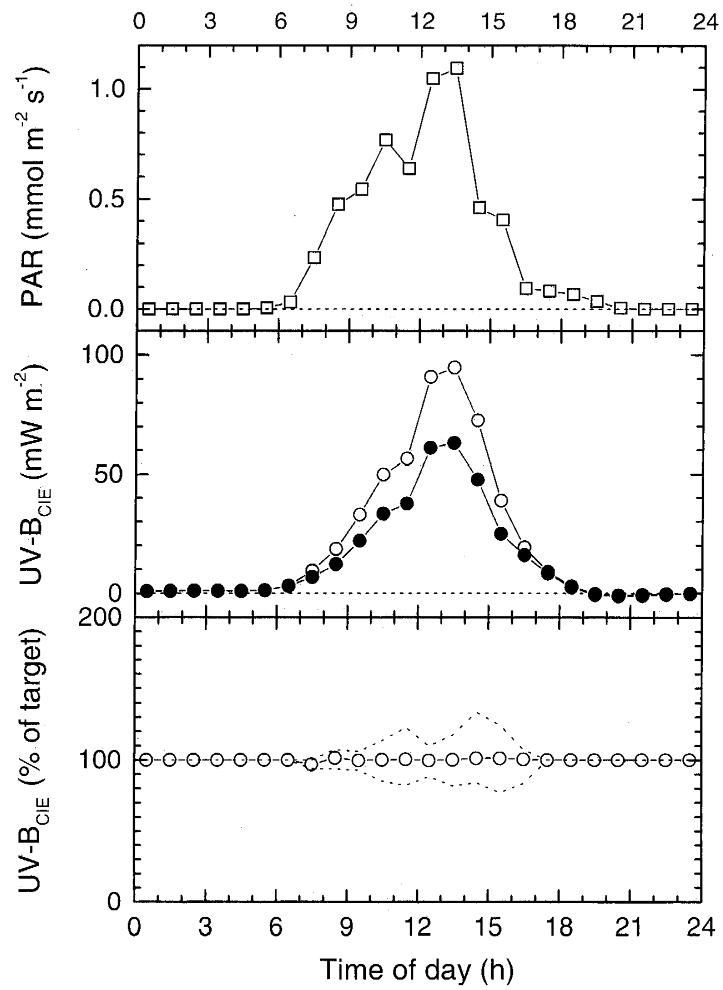

Fig. 8 Performance of the system on a sunny day. (a) Photosynthetically active radiation. Photon flux density measured with a Li–Cor LI–190 SA quantum sensor. (b) Ultraviolet–B irradiance, CIE weighted, under the lamps filtered with acetate (○) and under the lamps filtered with polyester (●). Program set to 50% increase in UV–B$_{CIE}$. (c) Relative irradiance under the lamps with acetate filter as a percentage of the target used to set the lamps during the previous minute (worse case values). The solid line and symbols indicate hourly means, the dashed lines the hourly maximum and minimum values.

Performance of whole system

The real precision of the system is limited by the spatial variation in solar UV–B between frames caused by shading from neigbouring objects. This effect is most important at low sun elevation angles, when UV–B irradiance is low. In this section we report on the *apparent* performance as measured by the two sensors used by the system. This is the performance of the controlled frames, and does not reflect the performance of slave frames (those without sensors), or any calibration errors of the sensors.

As an example of a sunny day we have taken 30 August 1997 (day 242) and as an example of partly cloudy day we have taken 26 August 1997 (day 238).

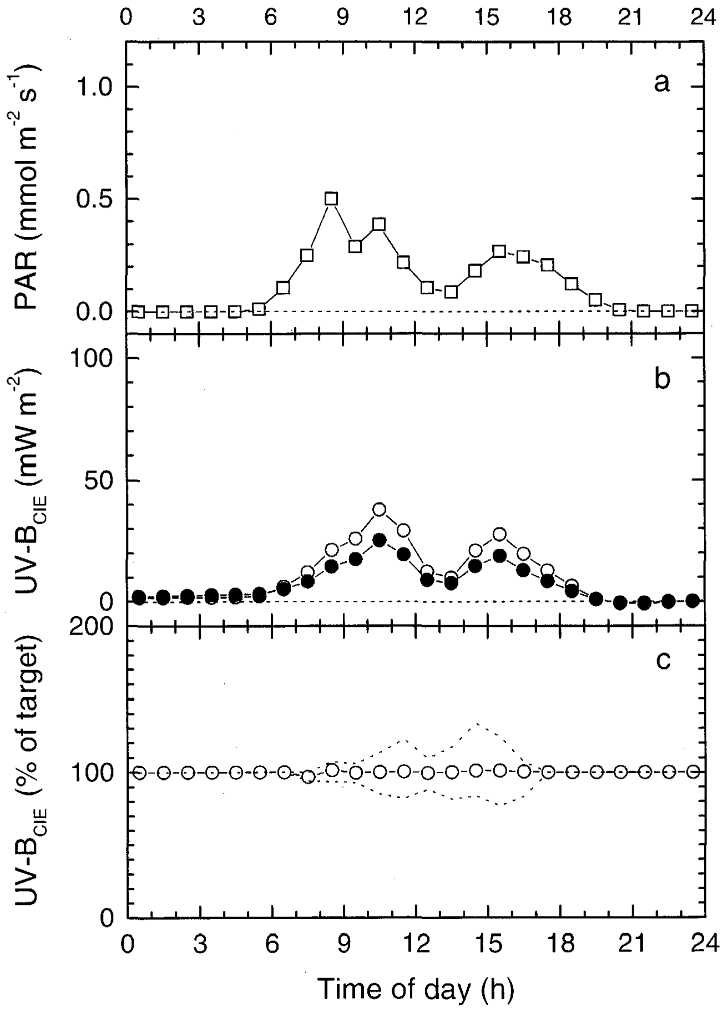

Fig. 9 Performance of the system on a cloudy day. (a) Photosynthetically active radiation. Photon flux density measured with a Li-Cor LI-190 SA quantum sensor. (b) Ultraviolet-B irradiance, CIE weighted, under the lamps filtered with acetate (○) and under the lamps filtered with polyester (•). Program set to 50% increase in UV-B_{CIE}. (c) Relative irradiance under the lamps with acetate filter as a percentage of the target used to set the lamps during the previous minute (worse case values). The solid line and symbols indicate hourly means, the dashed lines the hourly maximum and minimum values.

In the sunny day the maximum photon flux density of PAR and the irradiance of UV-B_{BE} (Fig. 8) were approximately twice as much as during the partly cloudy day (Fig. 9). However, because the system is modulated the increase in UV-B_{BE} irradiance was an almost constant proportion of the solar UV-B_{BE} throughout both days.

The logic of the program ensures that at the time the dimmer voltage is set, the UV-B_{BE} irradiance achieved under the lamps with acetate is within ±5% of the target value. But the question remains of what happens during the minute elapsed until the dimmer is readjusted. To measure this source of error UV-B_{BE}

is measured also immediately before adjusting the dimmer, and the ratio between the achieved value and the freshly calculated target value is a measure of the worst case system error. On average there was an almost perfect match between the target and achieved values, but some individual measurements deviated by as much as 30% as a consequence of shadows passing over the sensors (Figs. 8c, 9c).

SEASONAL CHANGE

The expected ozone depletion, and concomitant increase in UV–B, is not constant through the year. The largest proportional increase occurs, and will occur, in late winter and spring (*6*). The system as described does not attempt to simulate seasonal changes in stratospheric ozone depletion, as it has been recently done (*4*). This could be achieved by changing, weekly or monthly, the constant used to calculate the target UV–B_{BE}. The change could be done manually editing the program or the program could be extended with the calculation of the fractional increase in UV–B_{BE} as a function of the date. Although a modulated system makes it less necessary to frequently replace the aged acetate filters to maintain the target dose, it must be kept in mind that the ageing of the film nevertheless affects the transmission spectrum, and frequent replacement of films is necessary to avoid seasonal changes in the quality of the supplemental radiation.

SAFETY CONSIDERATIONS

To avoid the danger of electrical shock, the system is protected by a residual current switch (30 mA maximum allowed leak to earth) and all metal frames are connected to earth. The lamps used do emit some UV–C radiation down to 270 nm, but all UV–C is absorbed by the filters. Anyway eye exposure to UV–B at a distance of a few centimeters from the lamps, or prolonged exposure at larger distances may in the long-term have detrimental effects. For this reason everybody working near the lamps is required to use UV absorbing eyeglasses. Prolonged exposure of unprotected skin at close range is also avoided with clothing or UV-blocking sun cream. As the facility is located inside a public garden, it is fenced and kept locked at all times. Warning notices are posted on the gate and fence.

ACKNOWLEDGEMENTS

Dr. Andrew Sandford gave very useful feedback to our first ideas of how to build a modulated system controlled by a datalogger. Some ideas for improvement of our system were taken from Prof. Lars Olof Björn's independently developed system located at Abisko. Mr. Matti Savinainen assembled the first prototype. Mr. Timo Haavisto did the testing and comparison of ballasts from different manufacturers, specified many of the components and did all the wiring. Mr. Kari Mättä and the staff of the university workshop did the design and mechanical assembly of the frames. Mr. Peka Piroinen and the staff of the Botanical gardens helped prepare the place were the system was installed.

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REFERENCES

1. Björn L. O. (1991) *Photobiology*, vol. 2. Department of Plant Physiology, University of Lund, Lund.
2. Caldwell M. M., Gold W. G., Harris G., Ashurst C. W. (1983) A modulated lamp system for solar UV-B (280–320 nm) supplementation studies in the field. *Photochemistry and Photobiology* **37**, 479–485.
3. McLeod A. R. (1997) Outdoor supplementation systems for studies of the effects of increased UV-B radiation. *Plant Ecology* **128**, 78–92.
4. Mepsted R., Paul N. D., Stephen J., Corlett J. E., Nogues S., Baker N. R., Jones H. G., Ayres P. G. (1996) Effects of enhanced UV-B radiation on pea (*Pisum sativum* L) grown under field conditions in the UK. *Global Change Biology* **2**, 325–334.
5. Newsham K. K., McLeod A. R., Greenslade P. D., Emmett A. A. (1996) Appropriate controls in outdoor UV-B supplementation experiments. *Global Change Biology* **2**, 319–324.
6. Taalas P., Kyrö E., Jokela T., Koskela T., Leszczynski K., Rummukainen M., Damski J., Supperi A. (1996) Stratospheric ozone depletion and solar UV radiation in the Arctic and its potential impact on human health in Finland. *Geophysica* **32**, 127–165.