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Effects of lighting, semi-closed greenhouse and split-root fertigation on energy use and CO_2 emissions in high latitude cucumber growing

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Effects of supplemental lighting, semi-closed greenhouse and split-root fertigation on weekly to seasonal heat and electricity use and CO_2 emissions in cucumber growing were estimated in Finland. With moderate lighting (170 W m^{-2} above rows, 60 W m^{-2} inter-row) in a ventilated greenhouse, seasonal electricity and heat use (MJ kg^{-1} cucumber) were 20–50 and 10–25, 17–30 and 3–8, 38–55 and 10–18 in spring, summer and autumn to mid-winter, respectively. In summer, a semi-closed greenhouse improved energy use efficiency by 20–30% and split-root fertigation by 0–15%. Raising light intensity and applying inter-row lighting allowed higher yields in autumn to mid-winter without affecting electricity use efficiency. In other seasons, increasing the lighting decreased the efficiency. The emissions largely resulted from electricity use. Direct emissions (kg CO_2-eq kg^{-1}) based on propane and electricity from the national grid were 2.5, 1.5 and 3.3 in spring, summer and autumn to mid-winter, respectively. Efficiency of using solar and supplemental PAR was markedly lower in summer than in other seasons. The results provide profile of energy use and emissions and point to ways to reduce them.

Key words: cucumber, carbon footprint, supplemental lighting, semi-closed, light use efficiency

Introduction

The Nordic countries are the northernmost producers of greenhouse vegetables in significant volumes. In Finland, located mainly between 60 and 63 °N, 79 thousand tonnes (Kt) of vegetables were produced on 248 hectares in 2013 (Puutarhatilastot 2013). In Norway at similar latitudes or slightly to the south, in a maritime climate, the production was 30 Kt on 66 hectares in 2013 (Statistics Norway 2014, Horticultural production 2013). In Sweden 56 Kt vegetables were grown on 114 hectares in 2013 (Skörd av trädgårdsväxter 2013), and in Denmark 32 Kt were produced on 96 hectares in 2012, (Danmarks statistic 2014). In the Netherlands, a major European production area, at about 52 °N, 1701 Kt of vegetables were produced on 4881 hectares in 2013 (Statline 2014). In Alaska, which is at the same latitude as Finland, vegetables were produced on only 2.1 hectares in 2012 (US Department of Agriculture 2014). In Canada, where greenhouses are located mainly between 42 and 51 °N, 286 Kt of vegetables were produced on 574 hectares in 2013 (Statistics Canada 2013).

To establish year-round presence in the local market, growers in Norway and Finland have adopted intensive use of supplemental light. Major crops that are grown under additional light include leaf vegetables and cucumber, which respond well to the supplemental light, and tomato to a lesser extent. The lighting intensity has been substantially raised to improve productivity (Moe et al. 2006) and vertical distribution has been changed to improve electricity use efficiency (Hovi-Pekkanen and Tahvonen 2008). Production intensity of cucumber has been raised highest in Norway where industry-wide annual average yield was 76 kg m^{-2}. In Finland it was 62 kg m^{-2}, and in much milder climate of the Netherlands 65 kg m^{-2}. In Sweden and Denmark yields were lower, 46 and 36 kg m^{-2}, showing less production in winter. In Canada the yield was 50 kg m^{-2}.

In addition to supplemental light, yield level could be increased by growing in a semi-closed greenhouse. Substantial increase in energy efficiency has been shown to be attainable in a semi-closed greenhouse in Western Europe (de Gelder et al. 2010, de Gelder et al. 2012, Coomans et al. 2013). In Finland, yields were improved in summer by the semi-closed greenhouse (Särkkä et al. 2007, Luomala et al. 2008), but such a system has not been adopted by growers because of its high capital cost.

In a study by Jokinen et al. (2011) growth improvement was also obtained by applying split-root fertigation. The split-root fertigation, which has separate root spaces for water and nutrient uptake, has been developed to allow a better balance of nutrient uptake and transpiration under high transpiration demand (Jokinen et al. 2011).

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Heating contributes around 90% of global warming emissions of greenhouse vegetable production in cool mid-latitude climates such as in the Netherlands and Canada (Dyer et al. 2011, Montero et al. 2010, Raab and Brunklaus 2012, Torrellas et al. 2012). In the Mediterranean climate of Almería, Spain, greenhouse structure, auxiliary equipment and fertilizers are the major sources of emissions; heating contributes roughly one third of all emissions (Torrellas et al. 2012). At high latitudes, in Norway and Finland, where high production intensity is maintained by supplemental lighting, the lighting is the more important source of emissions (Katajajuuri et al. 2007, Verheul and Thorsen 2010).

To develop sustainability in cucumber production, information is needed how new technologies like inter-row lighting, semi-closed greenhouse, and split-root fertigation effect on energy use and emissions. This study aims to set a temporally dynamic reference for energy use and CO_2 emissions from heating and lighting for cucumber. The study provides seasonal information on the effect of technologies used for raising productivity: lighting solutions and intensities, substrates and semi-closed greenhouse. Results allow comparison to other countries at seasonal level and they can be used to break data from energy use surveys with annual resolution to shorter time intervals.

The research questions were as follows:

1. To assess the effect of greenhouse type (ventilated vs. semi closed) on energy use of cucumber production.

2. To assess weekly, seasonal and annual energy consumption of different supplemental lighting (top lighting vs. top lighting + inter-row lighting) and substrate (conventional substrate vs. split-root fertigation in inter-row lighting) solutions within greenhouse type (ventilated vs. semi closed) per area (m^2) and unit weight of cucumber.

3. To assess weekly, seasonal and annual CO_2-emissions of energy consumption within greenhouse type.

4. To evaluate the effects different supplemental lighting and substrate solutions on light use efficiency (LUE) to assess gaps between obtained and potential yields expressed as yield gap.

5. To compare energy consumption and CO_2-emissions per weight unit in Finnish cucumber production to production in other countries.

Materials and methods

Growing systems

Experiments were conducted by MTT Agrifood Research Finland in Piikkiö on the south-western coast of Finland (60°23'N, 22°33'E). At this site monthly mean temperature of the coldest month, February, is -5°C. Average daily maximum temperature exceeds 0°C in March, rises to 22°C in July and falls below 0°C in November–December. More details of Piikkiö's climate can be found by referring to weather data for the adjacent city of Turku.

Two greenhouse compartments in a single span greenhouse with glass ceiling and double polycarbonate walls were used: one ventilated and the other semi-closed, both of 130 m^2. In the ventilated compartment temperature and humidity were controlled by using pipe heating, ventilation, fogging and a screen with 40% transmissivity. In the semi-closed compartment heat and humidity were removed during daytime by a cooling and dehumidification system from late April to mid-October. In 2005 and 2006 air from the semi-closed compartment was circulated through a combined cooler and dehumidifier that resided outside the compartment (Särkkä et al. 2006). In later experiments a Novarbo® screen of falling droplets (Huttunen 2011) was used in the compartment. Capacity of the both systems was adequate to maintain the semi-closed compartment closed during daytime most of the days. The Novarbo® screen was based on free movement of greenhouse air to a screen of falling droplets that were cooler than the dew point temperature of the air. The air was cooled and dehumidified by convection and condensation on the droplets. The water from the screen was cycled outdoors to a pool where sensible and latent heat brought from the greenhouse was disposed of by circulating the water with sprinklers. From the pool the water was pumped back to the droplet screen.

In the compartments cucumber was grown year-round under supplemental lighting using a high-wire growing system. The wire was 3.2 m from crop base, top lights with 400 W high pressure sodium (HPS) bulbs (SON-T, Koninklijke Philips Electronics N.V.) 3.7 m from base, and 250 W (SON-T) inter-row lights 1.5 m from base. The lighting was used over an 18 hour period starting at 3 a.m. whenever global radiation fell below 150 W m^{-2}.

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Crops were scheduled in three seasons: spring, from February to May (weeks 8–20), summer, from May to August–September (weeks 22–35), and autumn, from September to January (weeks 39–3). There was always a break between successive crops. Greenhouse climate and moisture of substrate were measured using industry-standard sensors and controlled by an Itumic CAG control system (Itumic Oy, Finland). The system recorded conditions every 30 seconds.

Heating water flow (V, $m^3 s^{-1}$), temperatures (°C) in pipes to (T_i) and from (T_o) greenhouse compartments, and state of supplemental lights (S, 0/1) were recorded by the control system. Heating energy (Q, J) was calculated as:

$$Q = \rho * c_p * (T_i - T_o) * V * dt$$

where ρ is water density (g m^{-3}), c_p is specific heat (J g^{-1} °C) and dt is the data recording interval (s). Energy to supplemental lighting was derived from the state of the lights and the lighting power.

Solar radiation and photosynthetically active radiation (PAR) at the top of the canopy was estimated from recorded global radiation (W m^{-2}), solar position and screen opening (%). Vertical profiles of PAR inside the canopy from solar light and supplemental lighting were established by measuring with a LI-COR LI-190 quantum sensor (LI-COR Inc., Lincoln, Nebraska USA).

Experiments

In the ventilated and semi-closed compartments top lighting (190 W m^{-2}) was compared to combined top and inter-row lighting (170+60 W m^{-2} or 220+70 W m^{-2}), and a conventional substrate was compared to a substrate with split-root fertigation in inter-row lighting. The conventional substrate was a peat board, 9 cm thick, 20 cm wide and 100 cm long. Three plants were grown on it leading to a density of 2.3 plants m^{-2}. In the split-root fertigation the two root spaces contained similar peat boards as in the conventional substrate but only 10 cm wide. The spaces were irrigated separately with solutions of low (EC 1.2 dS m^{-1}) and high nutrient (EC 3.5 dS m^{-1}) concentration (Jokinen et al. 2011).

In total 11 experiments (labelled below A to K) with 32 combinations (labelled 1 to 32) of year, season, growing method and compartment were studied (Table 1). The compartments (ventilated or semi-closed) can be compared within same year but no statistical certainty can be assigned to the results because the compartments were not replicated.

Fruits were collected three times a week. Energy use per unit weight of fruit was computed weekly. Monthly mean energy use for heating and lighting were obtained from weekly mean uses by first calculating three-week moving averages with weekly weights 1, 2, 1, and then selecting the mid-point value each month. There were insufficient data points to calculate the moving average for February and September.

Climate

Minimum night temperatures were 19–20 °C, daytime minima 21–22 °C in both greenhouse compartments. The temperature that started ventilation or triggered cooling in semi-closed compartment was 25 °C. If the temperature rose above 28 °C despite cooling, ventilation began in the semi-closed compartment, too. In July, temperatures in the ventilated compartment peaked at 30–33 °C, whereas in the cooled compartment they were 2–3 °C lower.

Relative humidity was kept above 70–75% by fogging and below 80% by ventilation in the ventilated compartment. In the semi-closed compartment it was maintained at 85% by fogging whenever cooling was applied and was not reduced by ventilation if it did not exceed 87%. An energy and shading screen was gradually closed when global radiation fell below 20 W m^{-2}. Shading was used in the ventilated compartment in summer, but not in the semi-closed compartment.

Pure CO_2 was fed to crops to maintain CO_2 concentration at 800 to 1000 ppm when vents were opened to less than 15% of their maximum opening. Otherwise CO_2 was maintained at 400 ppm.

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Yield gap

Weekly light use efficiency (LUE) was computed by dividing PAR µmol m^{-2} received by crop by weekly yield in kg m^{-2}. PAR from solar light and supplemental top-light above the crop were added to PAR from inter-row lighting. The value of PAR in µmol m^{-2} from inter-row lighting was calculated from the electrical power of bulbs in W m^{-2} using a conversion factor of 1.65 derived from efficiency 1.72 µmol J^{-1} (Philips) and assuming 4% loss due to aging of the bulbs. To assess gaps between obtained and potential yields, theoretical crop assimilation was simulated (Appendix 1). Inputs to the assimilation were pre-set leaf area index (LAI) paths, vertical distribution of LAI and driving variables: solar PAR above the crop, PAR from supplemental lighting, temperature and CO_2 concentration.

Emissions from heating and lighting

Emissions from heating were based on use of heat energy converted to propane gas that had an emission factor of 64 kg CO_2-eq MJ^{-1}. Emissions from lighting were based on use of electricity and the emission factor of electricity from the Finnish national grid, 58 kg CO_2-eq MJ^{-1} (Motiva 2013). An approximation of emissions from Dutch cucumber production was made assuming that heat is produced by a combined heat and power generator (CHP), and the emission factor for electricity from the grid is continuously 90 g CO_2-eq MJ^{-1} (Bles and Wielders 2013). The method based on energy content suggested by Blonk et al. (2010) was used. Emissions for experiments by Lopéz et al. (2000) in Almería were based on natural gas with an emission factor of 56 kg CO_2-eq MJ^{-1}.

Statistical analyses

Replicated growing experiments in the ventilated and semi-closed compartments were tested pair-wise with t-test. Differences between the compartments could not be formally statistically tested because there were no replications of the compartments. However, variation of yields around their mean values, as measured by twice the standard deviation, indicates reliability of differences for similar lighting and substrate treatments between the compartments.

Results

Yield

During all the seasons in the ventilated compartment the weekly yields peaked first at 4–5.3 kg m^{-2} and then declined with aging of crops. In summer, the late season yields in August were 2–3.4 kg m^{-2}. In spring, the yields declined by May to 2.5 to 3.5 kg m^{-2}. Yields were lowest late in the autumn season, in December and in January, being 2–5 kg m^{-2} in the ventilated compartment (weekly yield data not shown). Despite higher weekly PAR, the summer yields were no higher than the yields obtained in spring and autumn. In summer the yield in the semi-closed compartment was 15–23% higher than in the ventilated compartment (Table 1, experiments C, D, H) with respective reduction in energy use per unit weight.

Weekly energy consumption

In all lighting combinations electricity consumption for supplemental lighting was 80–120 MJ m^{-2} a week for autumn and spring crops, and 20–60 MJ m^{-2} a week in summer. Weekly heating was around 1–15 MJ m^{-2} in summer, rose to 40–70 MJ m^{-2} by December and January, was 20–35 MJ m^{-2} in February and fell back to 1 – 15 MJ m^{-2} by May (weekly data not shown). The cycling of water by pumps and cycling of air by fans in the semi-closed compartment consumed 1–2 MJ m^{-2} of greenhouse electricity weekly from late April to early June and 2–4 MJ m^{-2} in June to September (data not shown).

In mid-winter (week 45–3), 20–50 MJ of electricity was used to produce one kilogram of fresh weight cucumber (Fig. 1). In summer, by week 25, the figure was 5–25 MJ kg^{-1}. The elevated outliers in Figure 1 resulted from low weekly yields after planting in February, June and October.

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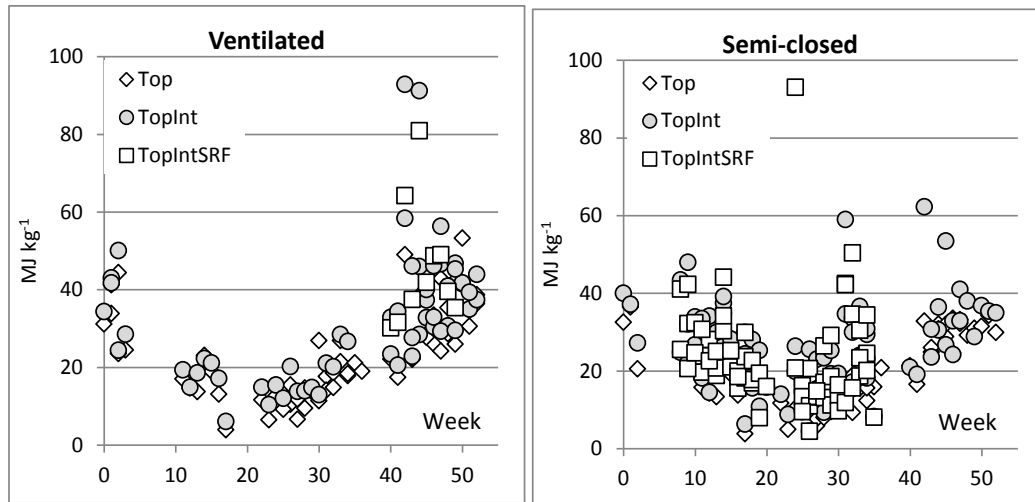
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Fig. 1. Weekly supplemental lighting MJ kg^{-1} fruit fresh weight. Top = top light, TopInt = top light + inter- row light, SRF = split-root fertigation.
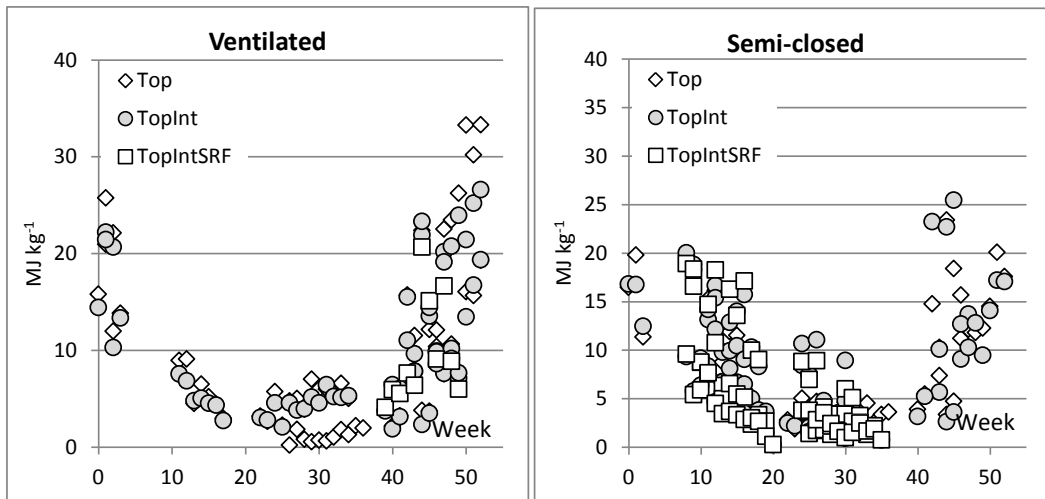

Fig. 2. Weekly heating MJ kg^{-1} fruit fresh weight. Top = top light, TopInt = top light + inter-row light, SRF = split-root fertigation.

Heating requirement per unit weight of fruit showed a similar annual pattern as the lighting use. In summer, in all but one experiment 35–50% more heating was used in the ventilated compartment than in the semi-closed. In one experiment the heating was much higher in the semi-closed compartment because of contradictory settings for dehumidification and heating in the semi-closed compartment (Table 1, experiment D).

As nearly all electricity used for lighting was ultimately converted to heat, virtually all energy was utilized as heat. Comparing data in the Figures 1 and 2 shows the proportion of heat provided by heating pipes and lights. In mid-winter, 35–45% of the heat came from heating pipes, and the rest from the lights. In summer, the weekly proportion of heat from the pipes ranged from 1% to 35%, being generally 20%.

Weekly emissions

The direct CO_2 emissions from supplemental lighting were 1.5–3 kg CO_2-eq kg^{-1} yield in mid-winter and around 1 kg in summer (Fig. 3). The emissions from the heating were roughly half of the emission from the lighting (Fig. 4).
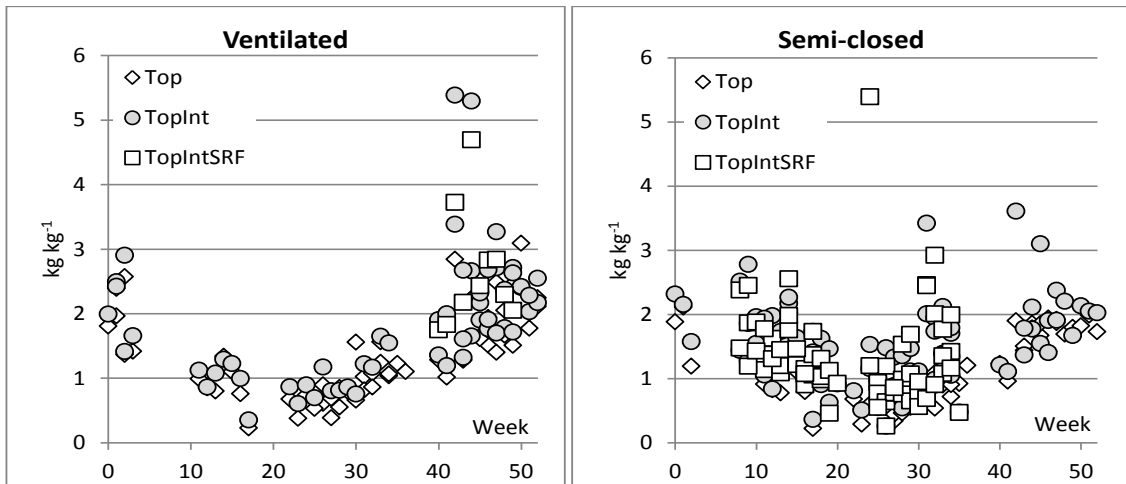
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Fig. 3. Weekly emission kg CO_2-eq per kg fruit from supplemental lighting. Top = top light, TopInt = top light + inter-row light, SRF = split-root fertigation.
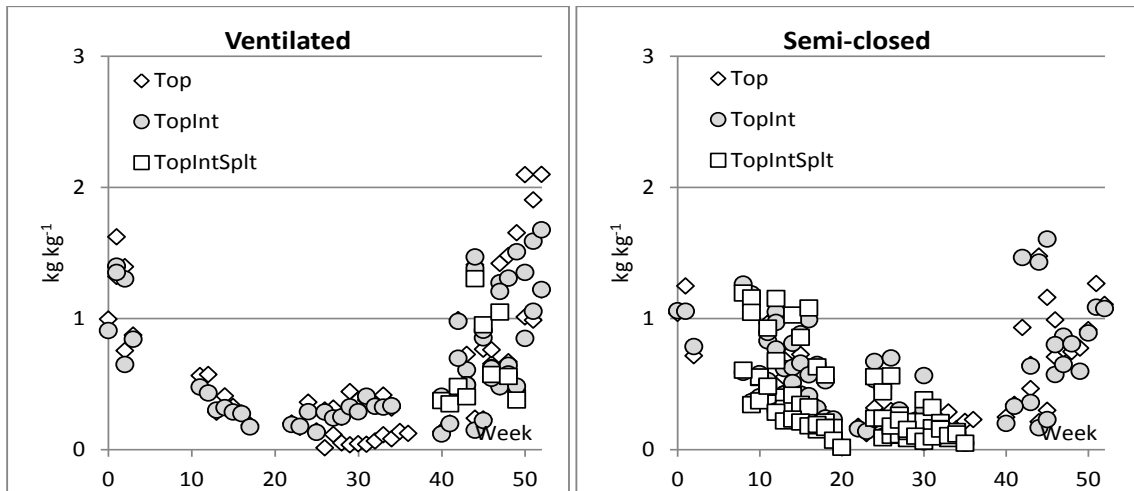

Fig. 4. Weekly emission kg CO_2-eq per kg fruit from heating based on propane gas fuel. Top = top light, TopInt = top light + inter-row light, SRF = split-root fertigation.

Seasonal and annual energy use and CO_2 emission

Solar radiation contributed 50–70% (74–85% PAR) of the total radiation for summer crops (Table 1). In spring, the sun provided 30–40% (44–59% PAR) and in autumn only 9–18% (18–33% PAR).

The energy use (Table 1) and emissions (Fig. 5) were highest for the autumn crops in both compartments. The values in Figure 5 do not include energy consumption during the seedling production phase. To accommodate that, the energy use figures for spring and summer crops should be increased by about 10%.

In experiment D in the semi-closed compartment, conflicting settings for humidity control by heating and temperature control by cooling led to anomalously high heat use and emission. Proper control in experiments C and H brought down the heat use. For autumn crops (week 39–3) the full seasonal values for experiments E and I (Table 1) were very representative, but experiments A and F were interrupted before mid-winter.

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Table 1. Yield and energy use during production phase in ventilated and semi-closed greenhouse compartments with four different growing methods. Column headings: Treatment id (1 to 32), experiment (A to K, experiments with same letter ran at same time), total electric power of top lighting + inter-row lighting W m^{-2}, substrate (C=conventional substrate, SRF=split root fertigation), compartment (Vent=ventilated, Semi=semi-closed), growing weeks (week of year), yield (yield over growing weeks), 2xStd of yield (2 x standard deviation of yield), light (electricity use for lighting over growing weeks), heat (heating over growing weeks), solar (solar radiation to crop over growing weeks). Where higher yield or lower electricity use was significantly different within a compartment, it is marked with an asterisk. Where 2 x Std (=standard deviation) indicates that comparisons V1–S1 to V5–S5 between ventilated and semi-closed compartments show real differences, yield and energy use are marked with superscripted V1 – S1 to V5 – S5.

Id	Experiment	Lighting W m^{-2}	Substrate	Compartment	Growing weeks	Yield kg m^{-2}	2xStd of yield	Light MJ kg^{-1}	Heat MJ kg^{-1}	Solar MJ kg^{-1}
Spring										
1	B	170+60	C	Semi	8..18	35.5	2.0	34.8	17.4	20.1
2	B	170+60	SRF	Semi	8..18	34.7	1.5	35.4	17.8	20.5
3	B	170+60	C	Semi	9..19	31.7	8.3	35.7	11.5	26.2
4	B	170+60	SRF	Semi	9..19	37.8	1.3	29.9	9.5	22.0
5	G	190	C	Vent	10..17	23.5	1.2	23.4	10.1	20.3
6	G	170+60	C	Vent	10..17	26.6	1.1	26.8	8.9	17.9
7	G	190	C	Semi	10..17	24.2	1.1	22.7	19.8	19.7
8	G	170+60	C	Semi	10..17	26.9	1.1	26.5	17.8	17.7
9	K	220+70	C	Semi	7..20	53.7	4.5	34.1	7.8	16.3
10	K	220+70	SRF	Semi	7..20	59.5	4.5	30.8	7.1	14.7
Summer										
11	C	170+60	C	Vent	24..34	24.1^{V1}	2.0	33.0^{V1}	7.8	58.9^{V1}
12	C	170+60	SRF	Vent	24..34	27.3*^{V2}	1.8	29.2*^{V2}	6.9	52.1^{V2}
13	C	170+60	C	Semi	24..34	31.1^{S1}	1.7	23.7^{S1}	3.5	45.7^{S1}
14	C	170+60	SRF	Semi	24..34	35.3*^{S2}	2.5	21.0*^{S2}	3.1	40.3^{S2}
15	D	190	C	Vent	25..37	35.1^{V3}	2.9	17.8^{V3}	1.4	30.1^{V3}
16	D	190	C	Semi	25..37	44.7^{S3}	3.3	14.1^{S3}	8.6	23.6^{S3}
17	H	190	C	Vent	21..34	37.8^{V4}	4.0	15.7^{V4}	5.6	54.7^{V4}
18	H	170+60	C	Vent	21..34	41.8^{V5}	2.0	20.0*^{V5}	5.1	49.4^{V5}
19	H	190	C	Semi	21..34	47.5^{S4}	2.6	12.5^{S4}	3.4	43.5^{S4}
20	H	170+60	C	Semi	21..34	49.2^{S5}	4.1	17.1*^{S5}	3.2	42.0^{S5}
21	J	220+70	C	Semi	23..35	46.8	3.0	21.2	2.8	35.7
22	J	220+70	SRF	Semi	23..35	46.5	3.9	21.4	2.8	35.9
Autumn										
23	A	170+60	C	Vent	39..49	20.4	1.7	55.6	10.7	10.5
24	A	170+60	SRF	Vent	39..49	22.1	1.9	51.2	9.8	9.7
25	E	190	C	Vent	42..03	28.6	5.7	41.4	21.4	6.9
26	E	170+60	C	Vent	42..03	34.3	3.8	42.5	17.9	5.7
27	F	190	C	Semi	43..47	13.4	2.3	43.7	15.9	12.7
28	F	170+60	C	Semi	43..47	16.6	1.6	43.8	12.9	10.3
29	I	190	C	Vent	40..02	42.7	2.4	32.7	11.8	7.2
30	I	170+60	C	Vent	40..02	44.5	2.2	38.2	11.5	6.9
31	I	190	C	Semi	40..02	43.5	3.6	32.2	14.3	7.1
32	I	170+60	C	Semi	40..02	45.4	1.8	37.5	13.6	6.8

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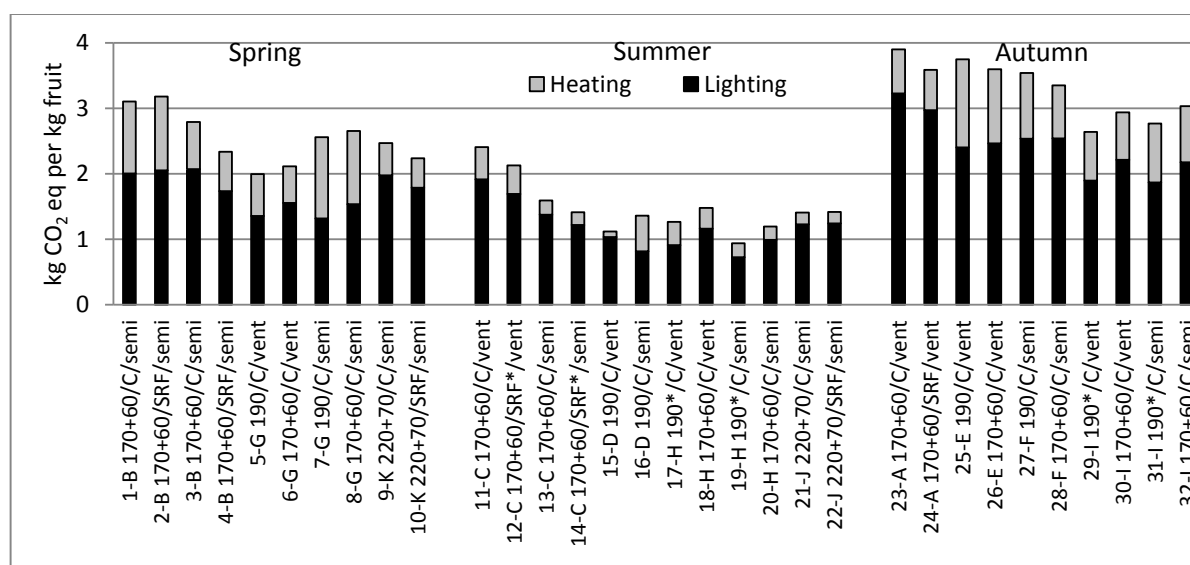T. Kaukoranta et al. (2014) 23: 220–235

Fig.5. Direct CO_2 emissions during production phase from lighting and heating (kg CO_2-eq per kg fruit) in ventilated and semi-closed greenhouse compartments with four different growing methods. X axis labels: treatment id (1 to 32), experiment (A to K, experiments with same letter ran at same time), total electric power of top lighting + inter-lighting W m^{-2}, substrate (C=conventional substrate, SRF=split root fertigation), compartment (Vent=ventilated, Semi=semi-closed). Where higher yield or lower total emission was significantly different within a compartment, it is marked with an asterisk.

Obviously, given the choice of fuel and electricity the dominant source of emissions in all systems was the lighting, which generated 65% of the emissions on average in mid-winter, 70% in spring and autumn and 85% in summer (Fig. 6).

The combinations of supplemental lighting, substrate (conventional or split-fertigation) and compartment (ventilated or semi-closed) that ran parallel in the same time (same letter A to K on vertical axis in Table 1 and in Fig. 5) can be directly compared for efficiency of energy use and emissions. In two experiments in autumn (E, F) (Table 1, Fig. 5) replacing top lighting of 190 W m^{-2} by top and inter-row lighting of 170 + 60 W m^{-2} did not affect electricity use MJ kg^{-1} but in one experiment (I) electricity use increased 16–17%. In spring electricity use increased 15–17% (G), in summer 27–37% (H). In terms of marginal gain from added electricity input (relative yield increase/ relative electricity increase) the results were: 0.86 (E), 0.99 (F), 0.19–0.20 (I), 0.37–0.45 (G), 0.09–0.26 (H). In experiment H the inter-row light was tested in parallel in the ventilated and semi-closed compartments. Considering the variation of yield (2 x Std) the effect on yield is similarly low in both compartments. The highest lighting intensity (220 + 70 W m^{-2}) resulted in rather high electricity use but no control treatment with lower intensity is available for comparison.

The split-root fertigation increased yields and thus directly reduced emissions 0–19% per weight unit of yield (A, B, C, K, J), but the effect was statistically significant only in summer in experiment C where the increase was 13%.

Annually, weighted averages (absolute yields as weights) for the heating and the lighting with 170 + 60 W m^{-2} lighting, were 9 and 32 MJ kg^{-1}, respectively. The split-root fertigation as compared to the conventional substrate increased annual yield and thus electricity use efficiency by more than 10%, but the effect was not consistent. The split-root fertigation increased yields in all experiments (A, B, C, K, J), but the increase was statistically significant only in summer in experiment C. The semi-closed compartment provided annually 5–7% more yield than the ventilated compartment.

Yield gap

Total solar and supplemental light was used more efficiently in spring and autumn than in summer (Fig. 6). In the semi-closed compartment light use efficiency (LUE) was better than in the ventilated compartment but still it was clearly lower in summer than in other seasons. The comparison of the simulated and observed yields (Fig. 7) shows that in summer the theoretical yields depart upwards from the observed yields. The difference was quite

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large, roughly 1 kg m^{-2} a week. The simulation did not take into account the possible reduction of yielding capacity with the aging of crops at the end of seasons.
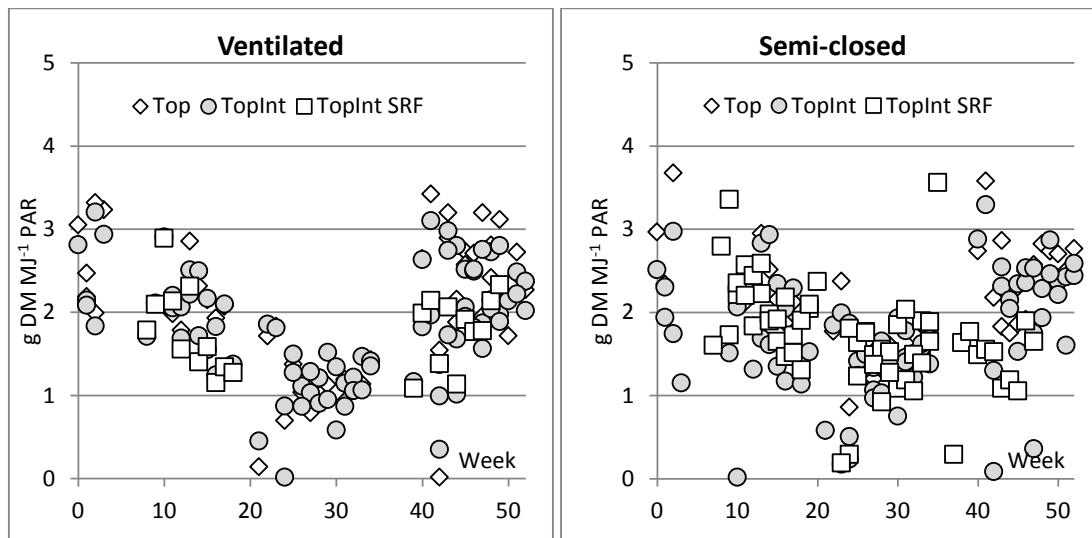

Fig. 6. Weekly light use efficiency (LUE): fruit dry matter production divided by MJ photosynthetically active radiation (PAR). Top = top light, TopInt = top light + inter- row light, SRF = split-root fertigation.
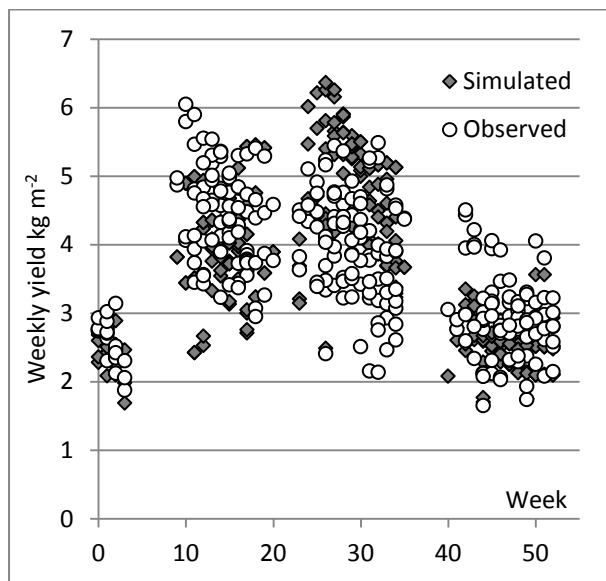

Fig. 7. Weekly observed and simulated yields of cucumber kg m^{-2} in all experiments.

Comparison with other production areas

Weighted monthly means for energy use in the experiments where lighting was 170 + 60 W m^{-2}, substrate was conventional, and the crops were grown at same time in the ventilated and semi-closed compartments, are presented in Table 2. For comparison, data from published experiments in other regions are shown. Direct emissions from heating and lighting which are estimated from the figures in Table 2 are presented in Table 3.

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Table 2. Seasonal energy use MJ kg^{-1} of cucumber use for lighting and heating in Finland, Canada, Netherlands and Spain in different production systems. Fin = Finland, CAN = Ontario, Canada, NL = Netherlands, ES = Almería, Spain. Vent = ventilated, Semi = semi-closed greenhouse, Suppl = supplemental lighting power, Heat = heating MJ kg^{-1}, Light = lighting MJ kg^{-1}. T12 = heating set point 12°C, T14 = heating set point 14 or 15 °C.

| | FIN[1] Vent | | FIN[1] Semi | | NL[2] Semi | | NL[3] Vent | ES[4] Vent | | CAN[5] Vent | |
| | Suppl 170+60 W m^{-2} | | Suppl 170+60 W m^{-2} | | Suppl 140 W m^{-2} | | No light | No light | | Suppl 170W m^{-2} | |
	Heat	Light	Heat	Light	Heat	Light	Heat	T12	T14	Heat	Light
Jan	12	27	13	26				13	24	12	49
Feb	-	-	-	-	7	35	29			11	37
Mar	5	12	6	18						10	40
Apr	4	15	6	16						0	23
May	3	13	4	15						0	23
Jun	3	15	4	15	5	10	5	-	-	0	26
Jul	5	16	3	14						0	31
Aug	5	24	2	20						0	32
Sep	-	-	-	-						0	36
Oct	12	36	13	36	9	16	18			1	44
Nov	14	41	12	35				13	24	9	47
Dec	21	39	20	36	-	-	-			11	57

(1) This study, (2) de Gelder et al. (2009), (3) Dieleman et al. 2007 (4) Lopéz et al. (2000), (5) Hao and Papadopoulos (2005).

Table 3. Direct emissions kg CO_2-eq kg^{-1} of cucumber growing in Finland, Netherlands and Spain estimated from energy use in Table 1. See column headings in Table 2.

| | FIN[1] Vent | FIN[1] Semi | NL[2] Semi | NL[3] Vent | ES[4] Vent |
| | Suppl 170+60 W m^{-2} | Suppl 170+60 W m^{-2} | Suppl 140 W m^{-2} | No light | No light |
	kg CO_2 kg^{-1}	kg CO_2 kg^{-1}	kg CO_2 kg^{-1}	kg CO_2 kg^{-1}	kg CO_2 kg^{-1}
Jan	2.3	2.3			0.7 – 1.3
Feb			3.8	2.3	
Mar	1.0	1.4			
Apr	1.1	1.3			
May	0.9	1.1			
Jun	1.1	1.1	1.4	0.4	
Jul	1.2	1.0			
Aug	1.8	1.3			
Sep					
Oct	2.9	2.9	2.1	1.4	
Nov	3.3	2.8			0.7 – 1.3
Dec	3.6	3.4			

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Discussion

Energy use

On an annual basis the electricity consumption for the combined inter- and top-lighting (170 + 60 W m^{-2}) was estimated to be about 32 MJ kg^{-1}. The calculated energy use did not include that for seedling production. Heat use was 9 MJ kg^{-1}. Due to the single-span structure of the experimental greenhouse, the heating was higher than it would have been in a block structure where smaller wall area might have saved 10–20% heat energy.

In spring, from February to May, and in autumn, from September to January, the greenhouse type – ventilated or semi-closed – did not have significant effects on the energy use efficiency. In summer, comparable experiments in the semi-closed compartment used 35–55% less heat and 14–28% less electricity when controlled properly. Overall gain for the electricity efficiency was a few percent lower because the electricity consumption of the cooling systems was 2–5% of the consumption of the lighting.

The split-root fertigation tended to improve yield in all seasons. Because no additional energy was used in the split-root fertigation, higher yields translated directly to better energy efficiency. However, the improvement was not consistent and it was statistically significant only in one experiment in summer. The highest effect in summer and strong variability was expected because the method improves water and nutrient uptake in periods of high solar radiation (Jokinen et al. 2011).

Applying inter-lighting and at the same time raising total electricity input from 190 W m^{-2} to 170 + 60 W m^{-2} improved yields without affecting electricity use efficiency in two experiments in autumn. However, in one experiment marginal gain from added electricity input (relative yield increase/ relative electricity increase) was very low, 0.2. This was a sunny autumn when crop started early. In spring the marginal gain was 0.37–0.45; in summer it was only 0.08–0.25 meaning that the added light was largely ineffective.

LUE was always lowest in summer. This was to be expected in the ventilated compartment where low CO_2 concentrations and high temperatures occurred at the same time. The semi-closed compartment raised significantly yields in summer but still LUE was clearly lower than in the other seasons. The comparison of the simulated and observed yields suggested that the low LUE in summer did not result only from low CO_2 concentrations relative to light intensity and temperature but there were other factors limiting growth.

Emissions from lighting and heating

Pursuing higher yields with higher lighting (170 + 60 W m^{-2} instead of 190 W m^{-2}) caused about 10% higher emissions in spring and 20–30% higher in summer. Annual emissions from the lighting (170 + 60 W m^{-2}) were 1.9 CO_2-eq kg^{-1} when electricity was drawn from the national grid. The heating of 9 MJ kg^{-1} created emissions of 0.6 CO_2-eq kg^{-1}, which could be mostly taken up by the crop if heat buffering in a reservoir was used. In a ventilated greenhouse the emissions were about 1.3 kg CO_2-eq kg^{-1} in summer, while in spring they were roughly 100% higher than in summer, and during the autumn seasons, September to January, they were 200% higher. In a well controlled semi-closed compartment the emissions were 25–35% lower in summer, mainly because of higher yields and slightly lower heating requirement. The effect of split-root fertigation on the emissions was directly proportional to yield increase.

The obtained annual emissions are similar to the values found in a survey by Mikkola (2006). Using the same emission coefficients for the survey data as in our experiments and setting a 10% share for raising seedlings, gave 2.2–3.0 kg CO_2-eq kg^{-1} in the production phase from a range of year-around production systems. In a study by Yrjänäinen et al. (2013) based on growers' data in four Finnish greenhouses annual emissions from energy use were 1.5–3.2 kg CO_2-eq kg^{-1}. They were caused by 6–10 MJ kg^{-1} of heating and 21–31 MJ kg^{-1} of lighting.

Comparison with other production areas

There are a very limited number of published experiments or surveys in other countries where energy consumption has been recorded. Annual variation that would allow good comparison with our results is not available in all cases but it is still interesting to compare magnitude of energy use in areas that directly compete with Finnish production or use similar technologies as is used in Finland.

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In Spain industry-wide average of direct energy use and emissions from it are lower than in Finland as the vast majority of growers do not use heating (García Martínez 2009). Lopez et al. (2000) measured energy use of a heated multi-tunnel greenhouse on a sand bed in Almería from November to March. It was 18 to 26 MJ kg^{-1} when cucumber yields ranged from 8 to 10 kg m^{-2}. Natural gas used in a heat blower in winter gives direct emissions of 0.7–1.3 CO_2-eq kg^{-1}, about 30–50% of the direct emissions in Finland at same time.

In the Netherlands, Dueck et al. (2004) estimated that annual heat use was 20.6 MJ kg^{-1} for an annual yield level of 75 kg m^{-2}. A similar figure was given recently in the project report of AgrEE (2012). Using that figure and the method based on energy content by Blonk et al. (2010, an emission value of 1.6 kg CO_2-eq kg^{-1} is provided, which is about 60% of that for Finnish year-round production.

Comparing our results with the experimental data of Dieleman et al. (2007) shows that in mid-winter and spring total energy use per unit weight of cucumber in the lighted greenhouse in Finland was lower than in the ventilated greenhouse in the Netherlands but higher in other seasons. In summer, when temperatures and total daily solar radiation are similar in both areas, lighting in our experiments raised energy use well above the Dutch level. In the autumn season, energy use is considerably higher in Finland, probably because of less solar light at the high latitude and high lighting intensity.

The differences are similar when the Finnish lighted greenhouse is compared with the Dutch semi-closed greenhouse with lighting (de Gelder et al. 2009). Any Finnish glass-covered greenhouse is virtually semi-closed from November to April because humidity is removed by a cold cover. The difference is mainly in the lower efficiency of electricity use for the lighting in Finland, which is likely caused by the more intense lighting.

Comparing emissions based on our experimental data with the emissions computed from the data of de Gelder et al. (2009) and Dieleman et al. (2007) shows that in January to March the emissions are lower in Finland than in the Netherlands regardless of greenhouse type in the Netherlands. Lighting in summer leads to higher emissions in the Netherlands than in Finland but lower emissions in autumn. Production without lighting in the Netherlands in summer and autumn causes about 50% lower emissions than the production with lighting in Finland.

Swedish production without supplemental lighting in the coastal region of Skåne is comparable in technology with Dutch production. Nationwide estimates of Davis (2011), based on data from Nielsen (2009) and a survey by Franzén et al. (2011) in Skåne, provide annual estimates of energy use. Heating stands for 18–26 MJ kg^{-1} and electricity use 0.8–1.1 MJ kg^{-1} energy consumption, resulting in annual mean emission from direct energy use of 2.6 kg CO_2-eq kg^{-1}.

In Norway, where the light climate is the same as in Finland, though temperatures are less extreme, similar technologies are applied in year-round production as in Finland. The figures reported by Verheul and Thorsen (2010) from surveyed commercial greenhouses are very near to those for Finnish energy use: 11 MJ kg^{-1} for heating and 32 MJ kg^{-1}for lighting. Because over 95% of electricity comes from hydropower (Statistic Norway 2013, Electricity, annual figures, 2012), the Norwegian emissions are the lowest in northern Europe: 0.7 kg CO_2-eq kg^{-1} if natural gas is used for the heating.

In southern Ontario, at 42°N, applying lighting in the greenhouse has resulted in substantially lower gain than in Scandinavia (Table 1). Hao and Papadopoulos (2005) experimented over two years with 170 W m^{-2} supplemental lighting to produce a maximum annual yield of 104 kg m^{-2}. Calculation of LUE (gram fruit dry matter per MJ solar + supplemental PAR) from their data showed that it was 10–15% lower in Ontario than in Finland from September to November, and from December to March about 30% lower. Probably, higher solar light from September to March in Canada than in Finland caused lower marginal gain from the lighting in Canada.

Conclusions

The semi-closed greenhouse and the split-root fertigation improved cucumber yields, and reduced energy use and emissions in summer. In other seasons a greenhouse covered by a single layer of glass can be maintained mostly closed without the semi-closed technology in Finland. In summer there seems to be other factors than direct effects of CO_2, PAR and temperature that restrain growth, even when cucumber is grown in the semi-closed greenhouse. Production with high lighting intensity is more efficient in Finland than at lower latitudes in Canada. In Spain direct energy use and direct CO_2 emissions are lower. In winter production in Finland does not need to

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cause essentially higher emissions than in the milder climate of the Netherlands. Yet, continuing intensive inter-row lighting in summer had a strong effect on the emissions. It can increase the emissions as much as the semi-closed greenhouse reduces them. Clearly, lighting intensity and distribution need to be controlled more optimally than in the experiments when HPS lighting was used. Expected next step of improving energy efficiency is partial or total replacement of HPS lights by LED lights that are expected to surpass efficiency of HPS in the coming years. Because lighting intensity has been raised so high in Finland that lighting has largely replaced heating, the adoption of significantly more energy efficient lighting technology will be bound to changes in heating systems, insulation and it calls for reconsideration of the effects of the semi-closed greenhouse.

Acknowledgements

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Appendix. Computation of potential fruit yields from LAI, radiation, ambient temperature and ambient carbon dioxide concentration.

1. Fruit growth rate, FGR (g s^{-1} m^{-2}).

$$FGR = (A_{cn} - R_{tc}) * 44.01/10^6 * (30/44) / 1.45 * HI * 1/DM$$

$$R_{tc} = 0.15 * A_{dn} /86400 * (1 - exp(-0.30*MAX(0, (T_a-10))))$$

$$A_{cn} = \Sigma_{Layer=1,N} A_n * LAI_{Layer}$$

A_{cn}, net assimilation rate of crop (g s^{-1} m^{-2}). R_{tc}, total respiration of crop (g s^{-1} m^{-2}). HI, harvest index (0.63). DM, relative fruit dry matter content (0.3 in winter, 0.32 in summer). A_{dn}, sum of net gross assimilation over past day (g/m^{-2}). T_a, daily mean ambient temperature (°C). A_n, leaf net photosynthesis rate at height Layer (µmol m^{-2} s^{-1}). LAI_{Layer}, leaf area at layer Layer (m^2).

2. Leaf net photosynthesis rate, A_n (µmol m^{-2} s^{-1}). A model for photosynthesis by Farquhar et al (1980).

$$A_n = MIN(A_c, A_j) - R_d$$

$$A_c = V_{cmax} * (C_i-Gamma)/(C_i+K_c*(1+O_i/K_O))$$

$$C_i = 0.8 * (1-exp(-0.0092*C_a)) * C_a$$

$$A_j = (J/4) * ((C_i-Gamma)/(C_i+2*Gamma))$$

$$J = Alfa * I / SQRT(1+Alfa^2 * I^2/ J_{max}^2)$$

A_c, A_j, assimilation rate limited by rubisco activity and by light, respectively (µmol m^{-2} s^{-1}). R_d, dark respiration (µmol m^{-2} s^{-1}). V_{cmax}, maximum carboxylation velocity (µmol m^{-2} s^{-1}). Gamma, CO_2 compensation point (µmol mol^{-1}). K_c, Michaelis constant for CO_2 (µmol mol^{-1}). O_i, internal leaf oxygen concentration (mmol mol^{-1}). K_O, Michaelis constant for O_2, (µmol mol^{-1}). C_i, C_a, internal and ambient leaf CO_2 concentration (µmol mol^{-1}). J, electron transport rate, (µmol m^{-2} s^{-1}). I, photosynthetically active radiation (PAR) at leaf layer (µmol m^{-2} s^{-1}). Parameters measured by Eeva-Maria Tuhkanen, MTT Agrifood Research Finland (unpublished): Alfa = 0.30 mol mol^{-1}, apparent efficiency of light energy conversion, J_{max} =210.0 µmol m^{-2} s^{-1}, light saturated potential rate of electron transport.

3. Leaf dark respiration rate, Rd (µmol m^{-2} s^{-1}).

$$R_d = 0.2 * exp(cRd - dHRd/(R*(T_a+273)))$$

$$V_{cmax} = 79 * exp(cVcmax - dHVcmax/(R*(T_a+273)))$$

$$Gamma = exp(cGamma - dHGamma/(R*T_a+(273)))$$

$$K_c = exp(cKc - dHKc/(R*(T_a+273)))$$

$$K_o = exp(cK0 - dHK0/(R*(T_a+273)))$$

V_{cmax}, maximum carboxylation velocity (µmol m^{-2} s^{-1}). Gamma, CO_2 compensation point (µmol mol^{-1}). K_c, Michaelis constant for CO_2 (µmol mol^{-1}). Ko, Michaelis constant for O_2, (µmol mol^{-1}). Parameters for temperature response of Rubisco limited photosynthesis by Bernacchi et al. 2001. cRd = 18.72, dHRd = 43.39, R = 8.31441e-3, cVcmax =26.35, dHVcmax = 65.33, cGamma = 19.02, dHGamma = 37.83, cKc = 38.05, dHKc = 79.43, cK0 = 20.30, dHK0 = 36.83.

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4. Total PAR at layer L, I_L.

$$I_L = I_s * \exp(-K_s * \Sigma_{L=1,L} LAI_L) + I_a * \exp(-K_a * \Sigma_{L=1,L} LAI_L) + I_b * \max(0, 1 - 4 * (H_L - H_b))^2$$

I_s, solar PAR. I_a, PAR from above-crop supplemental lighting. I_b, PAR from inter-row lighting. H_L, vertical distance from maximum height of crop (m). H_b, inter-row light suspension height (m). K_a, K_s, extinction coefficients for supplemental and solar light.

5. LAI of leaf layer L from top (L=1 to N, N=20), LAI_L.

$$LAI_L = RLS_L / (\Sigma_{L=1,N} RLS_L) * LAI$$

$$RLS_L = \max(0, \min(1, H - H_L))$$

H_L, vertical distance from maximum height of crop, H, crop height.