Calculation of NIR Effect on Greenhouse Climate in Various Conditions

F.L.K. Kempkes and S. Hemming
Wageningen UR Greenhouse Horticulture
Droevendaalsesteeg 1
6708 PB Wageningen
The Netherlands

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Abstract

In Northern regions of Europe glass is mainly used as greenhouse covering material whereas in Southern regions plastic films are commonly used. The development of covering material optical properties focuses on high light transmission, reduction of heating energy losses (higher latitudes) and reduction of cooling energy load by radiation (lower latitudes). Solar radiation can be divided into photosynthetic active radiation PAR and near infrared radiation NIR. Whereas the PAR is needed for crop growth and development, the energy fraction of the NIR heats the greenhouse and crop and contributes to transpiration, which is not necessarily always desirable during periods with high radiation. Materials or additives for greenhouse covers that reflect or absorb a fraction of the NIR radiation have become available on the market. Excluding NIR from the greenhouse will reduce the greenhouse air temperature. However, there are several side-effects of the reduction of NIR, which are important to consider, such as a higher energy use in winter and a smaller impact on reduction of heat load as expected because of the high NIR reflection of the crop itself. In this study model calculations of the effect on greenhouse climate of different NIR-absorbing prototype plastic films for the climatic conditions of Southern Spain are presented. The effect on greenhouse air temperature and humidity, and on crop transpiration are analyzed. The most appropriate application of a NIR-selective greenhouse cover for that climate is presented.

INTRODUCTION

Global radiation entering the greenhouse can be divided into ultraviolet radiation (UV, 300-400 nm), photosynthetically active radiation (PAR, 400-700 nm) and near infrared radiation (NIR, 700-2500 nm). Of the PAR waveband 95% is absorbed by the crop for photosynthesis and crop growth. NIR is partly (50%) reflected by the crop but will be absorbed by the construction elements of the greenhouse and indirectly increases air and plant temperature. More then 80% of PAR energy is not used for photosynthesis but is dissipated as heat. The heating effect from global radiation in greenhouses is fully beneficial during cold periods, but in warm periods the air and plant temperatures can increase to undesirable levels so that crop growth and production will be affected or even become impossible. By developing solid materials with NIR-filtering, like plastic films or glass for greenhouses (Verlodt and Verschaeren, 1997; Abdel-Ghany et al., 2001; Lopez-Marin et al., 2008) or sheets to be used as moveable screens (Runkle et al., 2002; Tanaka, 1997) or "whitewash" painting of the cover (von Elsner and Xie, 2003; Blanchard and Runkle, 2010), the heat load of the greenhouse can be reduced (Hemming et al., 2005, 2007). To obtain air temperature regulation during daytime, several options are available, among which ventilation (natural or forced), painting of the greenhouse cover, use of secondary covers, like a second film or shading nets and adding NIR-shielding products to the cover. All solutions except ventilation reduce PAR transmission into the greenhouse and, in turn, decrease photosynthetic activity. Therefore the ideal target is a NIR absorber/reflector, with a high PAR-transmittance. Recently, more sophisticated types of additives have been proposed, such as, interference pigments (Hoffmann and Waaijenberg, 2002), and surface-plasmon resonant (SPR) absorption nanoparticles (Schelm et al., 2005). These indicate good NIR selectivity with little effect on PAR transmission (Kaiser et al., 2002). SPR conducting nanoparticles have been suggested for use in spectrally selective glazing, having the advantage of fine tunability of the absorption characteristics. Several anti-reflection and low emission coatings for glass do have some NIR reflection (Kempkes et al., 2008, 2009). In this paper films containing NIR-absorbing pigments providing the SPR effect and their spectral characteristics have been analyzed. Computations have been made via an extensive greenhouse climate simulation model (KASPRO, De Zwart, 1996), of the heat and moisture fluxes inside greenhouse covered with such films. The most promising films will be evaluated and compared in a greenhouse in Almeria Spain.

MATERIALS AND METHODS

Model calculations of greenhouse climate and energy consumption were completed with the dynamic simulation KASPRO model (de Zwart, 1996). The model can simulate a full-scale greenhouse based on the construction elements, greenhouse equipment such as heating, cooling and misting, different covering materials and their properties (transmissivity, reflectivity, emissivity), set points for inside climate and the outside climate of a given location. Outputs are climate parameters, such as air temperature, relative humidity, CO_2 concentration and energy consumption. The model is based on the computation of all relevant heat and mass balances. Greenhouse climate is controlled by a replica of commercially available climate controllers. The model uses outside air and humidity, direct and diffuse radiation and sky temperature.

Outside climate data was provided by Estación Experimental Fundación Cajamar, Las Palmerillas, El Ejido, Almería Spain (36.8° N 2.4° W). Data included outside air temperature, humidity and global radiation. Additional data was gathered from the airport of Almeria climate station (http://www.wunderground.com/global/stations/08487.html) providing historical data of cloud cover. From this sky temperature and the amount of diffuse radiation was calculated. After validating the KASPRO model with Spanish climate data, the measured optical properties of the new covering materials were used as an input for the climate model. All calculations with prototype greenhouse films were completed without a heating system to obtain a passive greenhouse situation.

RESULTS AND DISCUSSION

Model Validation

The KASPRO climate model was originally based on a Venlo-type greenhouse. For this study was adapted and validated for a multi-tunnel type greenhouse (a multi-bay, arch roof, single plastic film covered greenhouse with sidewall ventilation). For that purpose data was provided by Estación Experimental Fundación Cajamar for a tomato crop transplanted on 20 September 2005 and ended 25 May 2006 within a 1000 m^2 multi tunnel greenhouse with side wall ventilation and a heating system. This greenhouse was covered with a commercial polyethylene plastic film with the properties as shown in table 1 (Commercial). The shown numbers are measured (new films provided by the supplier are used) in the laboratory of Wageningen UR greenhouse horticulture. This film had a UV block property (i.e. transmission in the UV range was only 20%). White wash paint was applied on the greenhouse reducing PAR by 25% after 15 March and 40% 15 April.

Model calculations provided a good correlation with measured data. Figure 1 shows the measured and calculated greenhouse air temperature and humidity and the outside conditions for the week of 25 October 2005. The calculated humidity is slightly overestimated during night. During day there is a good correlation. The dynamic of inside greenhouse temperature agrees well with outside temperature and global radiation. Humidity inside the greenhouse is a balance between sources and sinks. The source is the transpiration of the crop and calculated by the transpiration model without any adjustment to the local situation. The sink is mainly ventilation or leakage of the greenhouse when ventilators are closed and condensation on the cover. During night ventilators were closed. Calculated and measured temperatures match well during most days and nights whereas in some nights they show a mismatch of some degrees. This could be caused by inaccuracies in the calculated sky temperature, since cloud cover data was obtained from the airport which was 20 km away.

The fitted set of input parameters for KASPRO were used for all model calculations, without including either air heating or white wash shading.

Covering Materials

BASF developed several LDPE NIR-absorbing greenhouse films (series NIR 1 and NIR 2) at thicknesses ranging from 150 to 200 µm. The optical properties of these films in the UV, PAR and NIR wave band are shown in Figure 2 in comparison with those of a reference film without NIR filtering (Reference) and of a commercial film (Commercial) which was used at the experimental station and for model validation. The additives used for NIR 1 and NIR 2 series belong to two different classes of NIR absorbing particles formulated at increasing concentrations along the series. Although both particles utilize the same physical phenomenon of SPR (surface-plasmon resonant), the location of the resonance and its width are quite different. NIR 1 samples have a higher NIR solar energy attenuation (Table 1) compared to NIR 2 films, due to their SPR being located much closer to the visible light, where the solar NIR energy content is highest. NIR 2A has a low and NIR 2D a high density of these particles. As a drawback, by increasing the loading of the additive in the NIR 2 series, PAR transmission is also affected. The commercial film clear demonstrates the UV block pigment (Fig. 2).

Greenhouse Climate on a Typical Warm Sunny Day

Simulations of the effect of different NIR-absorbing plastic film coverings on greenhouse inside climate were completed. Five prototype films with properties shown in Table 1 were studied. The results from May 20th 2006, a clear day with a maximum temperature of 27°C and a maximum global radiation of 900 W m^{-2} can be seen in Figure 3. The daily integrated outside solar radiation for this day was 2379 J cm^{-2}. The NIR-absorbing films decreased the inside radiation available to the crop by 36% for NIR 2D compared to the reference (Fig. 3A). Although film NIR 2D provided the lowest heat load, the greenhouse air temperature increased by 3°C compared to the reference (Fig. 3B and C). This can be explained by an increased cover temperature caused by increased absorption, as shown in Figure 3D. The film cover became a heat sink for greenhouse air. The energy of the film cover was released by convection and radiation to the outside depending on wind velocity and emission coefficient of the cover. If the cover temperature is higher than greenhouse inside air temperature, though, the cover becomes a heat source for the air (by convection) and the plant canopy (by radiation). This was the results for films NIR 2A and 2D which had a high NIR absorption. Indirectly the high cover temperature is the reason greenhouse air temperature still increases, even while radiation load inside the greenhouse decreased.

The energy balance of the greenhouse air showed only a slight decrease of the heat loss by ventilation. The ventilators were fully opened so the ventilation rate was probably the limiting factor for obtaining additional natural cooling. It would be expected that increase of ventilation rate would result in decrease of the air temperature.

NIR-absorbing film prototypes reduce the transmission of short wave radiation on the crop. This radiation is the main energy source for crop transpiration. While the cover temperature is increased the radiation flux between cover and crop increased as well. As long as the cover temperature is higher than the crop temperature this cover will heat up the canopy by radiation. Under the reference and commercial films the cover temperature was lower than crop temperature and the crop lost energy to the cover. These fluxes were sufficiently large that the fluxes of short wave radiation to the canopy were nearly cancelled. For this reason only small effects on transpiration were shown (Fig. 3E). Despite a lower energy load an increase of plant transpiration was shown for NIR 2A.

Finally it is the crop growth which is the most important factor, thus a simplified photosynthesis model for biomass production of dry weight was used and is shown in

Figure 3F. This photosynthesis model was based on canopy temperature and CO_2 and did not account for fruit load of the crop. Therefore, the model can only indicate an increase or decrease of photosynthesis rates. The slow decrease in evening and night is due to crop respiration. An overview of the most relevant parameters is presented in Table 2.

Greenhouse Climate on a Typical Clouded Winter Day

The simulation results for a cloud covered rainy winter day, the outside solar radiation sum was 104 J cm^{-2} and the outside air temperatures ranged between 7 and 11°C are shown in Table 2. Different interactions between cover and inside climate can be observed from those shown in Figure 4. The NIR 2D film provided a large decrease in greenhouse air temperature compared to the other films, as it reduce inside air below outside air temperature (Fig. 4B). For this reason windows were opened to 20% as it is common practice in passive greenhouses to start ventilation when inside air temperature drops below outside air temperature. Even with the ventilation, the temperature increase compared to outside was limited. This is probably due to the limited air exchange with natural ventilation by roof ventilators in case of a negative temperature difference situation. Side wall vents could have helped. Differences in cover temperature are small in Figure 4D, whereas they were high with high radiation levels. Despite these small cover temperature differences the low greenhouse air temperature with the NIR 2D film was remarkable. During November and December soil temperature became colder with the NIR 2D and NIR 2A films, and thus was not an important heat source anymore.

At inside air humidity of 95%, the ventilation was activated to decrease humidity. Therefore, during night and early morning ventilators were slightly opened in greenhouses covered with NIR 1 and NIR 2A films.

The solar radiation during this day was very low, and the crop was unable to produce the energy sufficient for maintenance respiration, thus the net production of sugars was negative for the day (Fig. 4F).

The long term effect on average greenhouse air temperature was displayed in Figure 5. From November until February there was a lack of daily solar energy which limited the greenhouse air temperature. From September through October, and after February, the greenhouse air temperature was controlled by the activation of the ventilators to overcome the daily excess of solar energy. The temperature of the greenhouse during November through February could maybe be improved by using another climate control strategy, not implemented in this study. Furthermore, by the reduction of the solar energy load, the need for ventilation based on air temperature was decreased, but there was still a need for ventilation based on humidity. Therefore by ventilating the greenhouse to reduce excessive humidity, the air temperature is decreased many times because of the cool outside air temperature.

CONCLUSIONS

NIR absorbing greenhouse coverings were able to exclude specific wavebands of the solar radiation. However, their effect is limited, and in fact, NIR reflection would be more favorable. The exclusion by reflection of NIR energy from the greenhouse must be increased, since the crop itself is already a good NIR reflector (45%). The PAR transmission of greenhouse film covers needs to be high for winter crop production in Spain. During the winter cold periods, the NIR absorption negatively influences the greenhouse air temperature within passive greenhouses.

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Tables

Table 1. Transmission (perpendicular), absorption properties (fraction) and emission coefficients of five polyethylene plastic films.

Transmission	NIR 1	NIR 2A	NIR 2D	Reference	Commercial
Global 300-2500 nm	0.63	0.74	0.60	0.86	0.80
UV 300-400 nm	0.70	0.70	0.51	0.85	0.20
PAR 400-700 nm	0.86	0.81	0.69	0.88	0.85
NIR 700-2500 nm	0.59	0.73	0.59	0.85	0.82
Absorption					
Global 300-2500 nm	0.08	0.15	0.32	0.02	0.07
PAR 400-700 nm	0.03	0.11	0.24	0.02	0.03
NIR 700-2500 nm	0.12	0.19	0.39	0.01	0.03
Emission	0.37	0.29	0.35	0.60	0.70

Table 2. Results a cloud covered day (Winter (W), 10 January 2006), and a warm sunny day (Summer (S), 20 May 2006).

	NIR 1		NIR 2A		NIR 2D		Reference		Commercial	
	W	S	W	S	W	S	W	S	W	S
Global radiation on crop [J/cm^2]	50	1627	47	1571	32	1164	57	1801	54	1729
PAR radiation on crop [J/cm^2]	28	876	25	832	20	667	29	899	27	861
Mean greenh. temp. [°C]	10.7	24.2	10.9	24.4	8.3	24.2	10.6	24.2	10.4	24.2
Max greenh. temp. [°C]	11.4	33.6	11.6	34.2	9.5	34.3	11.4	33.6	11.3	33.6
Min greenh. temp. [°C]	9.5	17.3	9.7	17.3	6.9	16.9	9.4	17.3	9.3	17.2
Mean cover. temp. [°C]	9.2	23.7	9.6	25.4	9.1	28.4	8.7	22.2	8.6	22.4
Max cover temp. [°C]	10.4	34.4	10.6	39.4	11.2	48.5	10.2	29.6	10.1	30.3
Min cover Temp. [°C]	7.8	16.2	8.1	16.3	7.3	16.1	7.3	16.2	7.3	16.2
Cool load by crop [kJ/m^2]	257	4231	247	4339	144	4040	297	4288	281	4202
Net biomass prod. [g]	-0.2	29.3	-0.2	28.2	-0.2	25.0	-0.2	29.7	-0.2	29.1

Figures

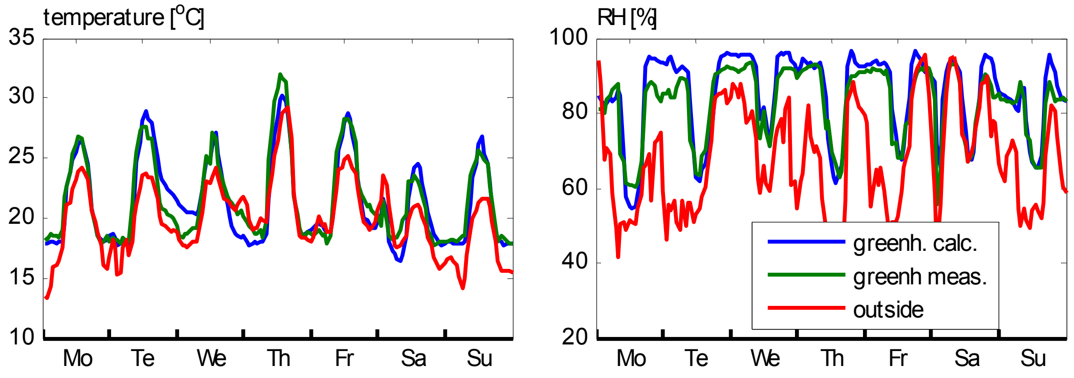

Fig. 1. Calculated (KASPRO model) and measured (Almeria, Spain) greenhouse air temperature and humidity for the week of 25 October 2005.

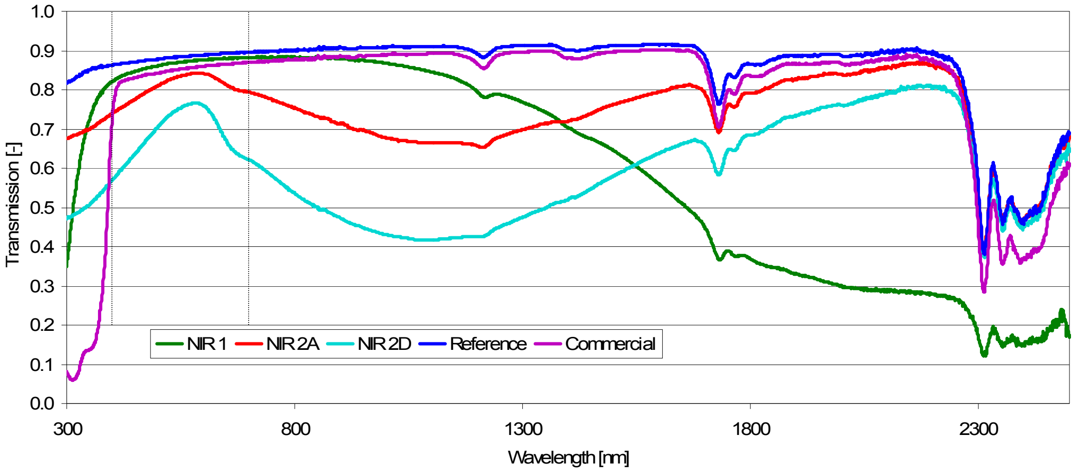

Fig. 2. Solar radiation transmission spectra of five plastic films.

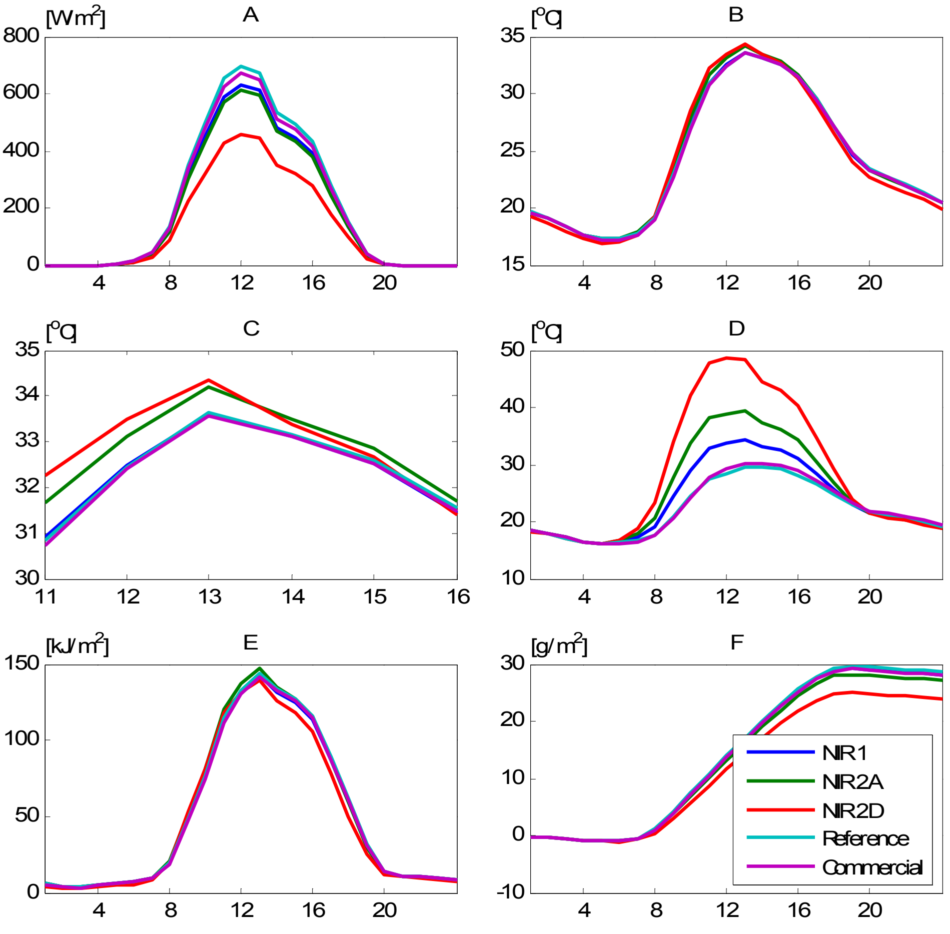

Fig. 3. Global radiation inside the greenhouse [A], Greenhouse air temperature [B], detail of greenhouse air temperature from 1:00 - 16:00 [C], greenhouse cover temperature [D], cool capacity by the crop [E] and crop biomass production [F] on 20 May 2006.

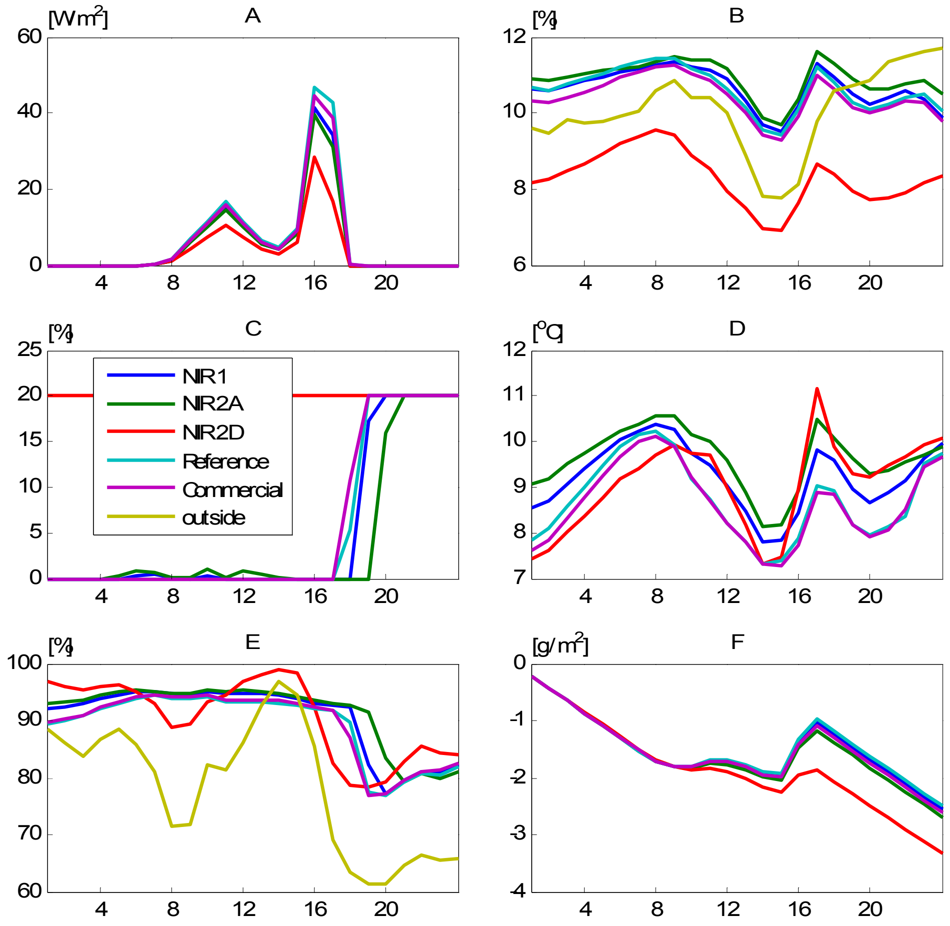

Fig. 4. Global radiation inside the greenhouse [A], Greenhouse air and outside air temperature [B], window opening [C], greenhouse cover temperature [D], relative humidity [E] and crop biomass production [F] on 10 January 2006.

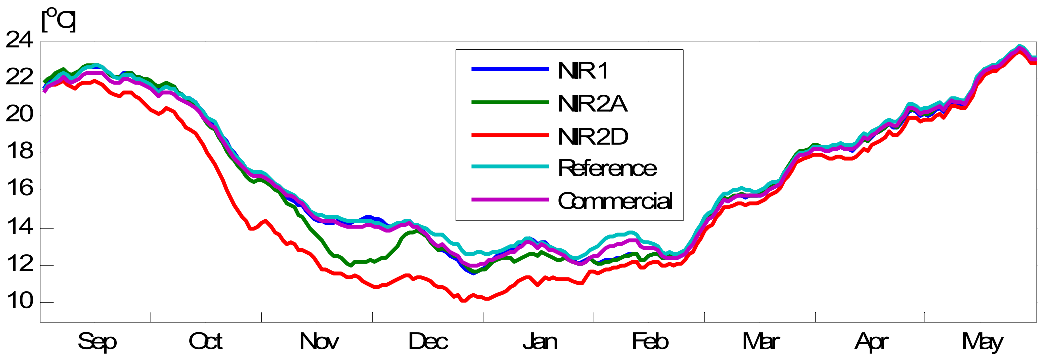

Fig. 5. Daily average greenhouse air temperature during the cropping cycle (7 day moving average).