Numerical Model to estimate the Radiometric Performance of Net Covered Structures

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Abstract

The design of structures to support nets for agricultural applications is mostly empirical. The radiometric behaviour of a net covered structure strongly depends on the shape of the structure, the postion of the sun and the external light conditions and the radiometric performance of net itself (Castellano et al. 2006). Nets are three-dimensional objects, the optical properties of nets can be different for different angles of incidence, the optical properties may change depending on the external light condictions (clear / overcast sky). The colour of the nets is important for the plant growth (Oren-Shamir et al. 2001). Transparent or semitransparent threads may be used for a high light level inside the net structure, green or black nets may be used for reducing excessive solar radiation and generate mild and more uniform internal light conditions. For these reasons, a light model is developed analysing the radiometric performance of a structure covered with nets. The radiometric properties of the permeable cladding measured will be used in this model for estimating the overall performance of the structure on crop level. The objectives of the use of a light model were: Estimating the year-round light interval of a net structure on plant level; Analysing the optical properties of different net structures during different seasons and different times of the day; Developing a simple method to estimate the optical properties of a net structure relevant for plant growth, use that as a tool for producers and growers.

Introduction

The design of structures to support nets for agricultural applications is mostly empirical so far. Until now investigations of radiometric properties of nets or net covered structures are very limited. While the air flow resistance of different kind of insect nets and some structures covered with insect nets is investigated by various research groups (Bailey et al., 2003; Demrati et al., 2001; Fatnassi et al., 2003; Fatnassi et al., 2002; Harmanto et al.; 2005; Klose and Tantau, 2004; Miguel et al. , 1997; Miguel, 1998; Soni et al., 2005; Teitel, 2007; Teitel et al., 1996; Valera 2005), only little is known about the radiometric properties of different net types (Castellano et al., 2007) or total net covered structures (Castellano et al., 2006).

However, the radiometric properties of agricultural net structures are very important since they influence directly the agricultural crop production. So far published data on in situ measurements of the radiometric conditions inside net covered structures are lacking. The radiometric properties of any covering is very important and can be characterised by several figures, such as transmissivity, reflectivity and absorption of different wavelengths of the sunlight (Hemming et al., 2006; Hemming et al., 2004; Kittas and Bailey, 1998; Pearson et al., 1995). Moreover, nets are three-dimensional objects, the optical properties of nets can be different for different angles of incidence, optical properties may change depending on the external light conditions (clear / overcast sky). The colour of the nets and the transmitted light spectrum is important for the plant growth (Elad et al., 2007; Oren-Shamir et al. 2001; Shahak and Gussakovsky 2004; Shahak et al. 2004; Shahak et al., 2007). Transparent or semitransparent threads may be used for a high light level inside the net structure, green or black nets may be used for reducing excessive solar radiation and generate mild and more uniform internal light conditions.

The radiometric behaviour of a net covered structure strongly depends on the radiometric properties of the nets itself (Castellano et al., 2007), but also on the shape of the structure, the position of the sun and the external light conditions. Numerical models help to predict the performance of agricultural structures and can predict the radiometric performance. Such models were developed in the past for greenhouses covered with different kinds of covering materials, models can be simple (Impron et al., 2007; van den Kieboom and Stoffers, 1985; de Zwart, 1996) or more complex based on the ray-tracing method (Farkas et al., 2001; Swinkels et al., 2001). For estimating the radiometric performance of net covered structures more detailed models are needed.

For these reasons, a light model is developed analysing the radiometric performance of a structure covered with nets. The radiometric properties of the permeable cladding measured will be used in this model for estimating the overall performance of the structure on crop level. The objectives of the use of a light model were:

(1) Estimating the year-round light interval of a net structure on plant level

(2) Analysing the optical properties of different net structures during different seasons and different times of the day

(3) Developing a simple method to estimate the optical properties of a net structure relevant for plant growth, use that as a tool for producers and growers

Materials and Methods

Light transmission model

A light transmission model (RAYPRO) is developed by Wageningen UR Greenhouse Horticulture analysing the radiometric performance of a structure covered with nets. This model computes the light transmission through any object that can be represented by a set of parallelogram or triangular planes. RAYPRO is written in MATLAB (The Mathworks Inc, 1996) and is based on ray-tracing, a method by which a single ray of light is traced from the light source through the object or the other way around. The interaction of the ray of light and the material (net or construction elements) is calculated from the optical properties of the materials used and physical principles (Fresnel's equations). The geometry of the object is compiled to a set of planes, represented by vectors, as described by Swinkels et al. (2001). With the angle of incidence, as deducted from the vector calculations, the refraction index and light absorption by the material, the transmitted and reflected rays are constructed. A handy feature of the model is the re-entrance of rays, which makes it possible to reduce an object to the smallest repetitive component. In other words, a ray leaving this component on the right side, re-enters it from the left side as if it were the nearby component. The direct transmission of a beam of light is computed by representing it by a large number of rays, which enter the structure according to their angle of incidence defined by the shape of the construction, the azimuth and the elevation of the sun. Diffuse transmission is calculated by taking the weighted average of the direct transmissions of a series of azimuths and elevations.

A general description of the working principle of the model RAYPRO is given by Figure 1.

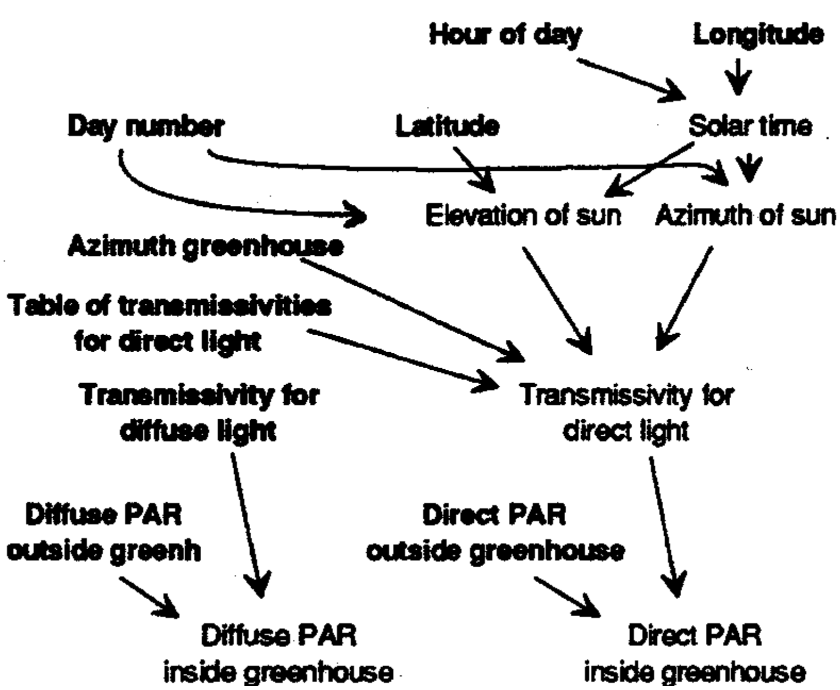


Figure 1 Principle of the light transmission model developed by Wageningen UR Greenhouse Horticulture to analyse the radiometric performance of net covered structures

Input parameters of the light model RAYPRO are:

- Latitude, longitude, hour of day, elevation of the sun, azimuth of sun
- Outside radiation: quantity of direct and diffuse radiation
- Geometry and orientation of the structure, azimuth of the roof
- Geometry and position of construction elements
- Radiometric properties of the nets as measured in the laboratories

Latitude, longitude, hour of day, elevation of the sun, azimuth of sun

The azimuth and elevation of the sun can be calculated for every hour of the year for a specific location. Together with the shape of the net construction, the angle of incidence of the sun on every part of the net construction can be determined. Knowing the transmission of the net for that angle of incidence and knowing the amount of sun radiation at that moment, the amount of light inside the construction can be determined.

Outside radiation: quantity of direct and diffuse radiation

An important input parameter for the light model is the outside radiation of a special location. A dataset is available for De Bilt (close to Amsterdam), The Netherlands (SEL-year as defined by Breuer and van de Braak, 1989). Other datasets can be added to the model. In general the global radiation can be divided into a direct and a diffuse part. This is shown in Table 1, which gives the total global radiation per period of the year in Bari and The Netherlands (SEL-year as defined by Breuer and van de Braak, 1989). It also gives a division of the total global radiation into the diffuse and direct part. To estimate the amount of light available for the crops, not the total global radiation (300-2500nm) is important but the amount of photosynthetic active radiation (PAR, 400-700nm). The model calculates the amount of PAR, again divided into the direct and the diffuse part for every hour of the year. The global radiation of the region and the amount of PAR outside are used is important input parameters of the model. The next step is to determine the quantity of diffuse PAR and the quantity of direct PAR, which is able to penetrate into the net structure. This is depending on the construction itself and the optical properties of the nets. For the analysis of different nets within this project the global radiation of Bari, Italy was taken as an input parameter. The global radiation was measured at the University of Bari throughout the year 2000 and can be characterised by the figures given in Table 1. The total global radiation per year is about 5250 MJ/m^2, about half of it is direct radiation and half of it is diffuse radiation. The amount of direct radiation is higher in the summer months than in the winter months. While the amount of global radiation in summer is more than 700 MJ/m^2 it is only 200 MJ/m^2 during winter months. In the same table the figures for De Bilt, The Netherlands, are given. Here the total global radiation per year is only 3650 MJ/m^2 and only a third of the global radiation year-round is direct, the rest is diffuse.

Table 1 Characterisation of the global radiation in Bari (left) compared to De Bilt (right)

Month	Global radiation total	Global radiation direct	Global radiation diffuse	Amount direct	Amount diffuse
	in MJ/m^2	in MJ/m^2	in MJ/m^2	%	%
Jan.	202.4	86.5	115.9	42.7	57.3
Feb.	180.8	83.0	97.8	45.9	54.1
Mar.	414.2	239.3	174.9	57.8	42.2
Apr.	487.4	270.3	217.0	55.5	44.5
May	645.3	348.8	296.5	54.1	45.9
Jun.	708.6	401.6	307.0	56.7	43.3
Jul.	736.0	392.5	343.5	53.3	46.7
Aug.	664.1	310.6	353.5	46.8	53.2
Sep.	428.5	162.8	265.8	38.0	62.0
Oct.	321.0	96.1	224.9	29.9	70.1
Nov.	238.6	36.5	202.2	15.3	84.7
Dec.	221.3	9.1	212.2	4.1	95.9
Total	**5248.3**	**2437.0**	**2811.2**	**46.4**	**53.6**

Month	Global radiation total	Global radiation direct	Global radiation diffuse	Amount direct	Amount diffuse
	in MJ/m^2	in MJ/m^2	in MJ/m^2	%	%
Jan.	63	13	50	20.5	79.5
Feb.	105	16	89	15.0	85.0
Mar.	315	95	220	30.2	69.8
Apr.	299	42	258	13.9	86.1
May	568	162	406	28.6	71.4
Jun.	552	159	393	28.8	71.2
Jul.	597	245	353	41.0	59.1
Aug.	503	148	354	29.5	70.5
Sep.	342	124	218	36.2	63.8
Oct.	164	38	126	23.1	76.9
Nov.	90	26	64	28.9	71.0
Dec.	54	14	40	26.6	73.4
Total	**3650**	**1081**	**2569**	**100**	**100**

Geometry of the net construction

A net covered greenhouse construction was built in at the University of Bari, Italy. The construction is described in Figure 2. It consists of two gothic-arched spans with a width of 9.63m, a total length of 30.80m and gutter height of 3.11m. The construction is orientated with ridge direction North-South. The construction is covered with four different types of nets: Libeccio 60 black/green, Ombraverde 50 green and Scirocco 50 black, Agriombra 50 black. The construction is modelled and analysed in the new developed light model RAYPRO (Figure 4). The shape of the construction is an important input factor for the model to determine the angle of incidence of the sun on every part of the construction. In the model calculations it is assumed that the whole construction is covered with a particular type of net. Calculations are carried out for the different types of nets. For evaluation purposes in situ measurements are carried out in the full-scale screen house using a spectroradiometer, which was able to measure the spectral transmission during different times of the day, in different seasons under the four different nets.

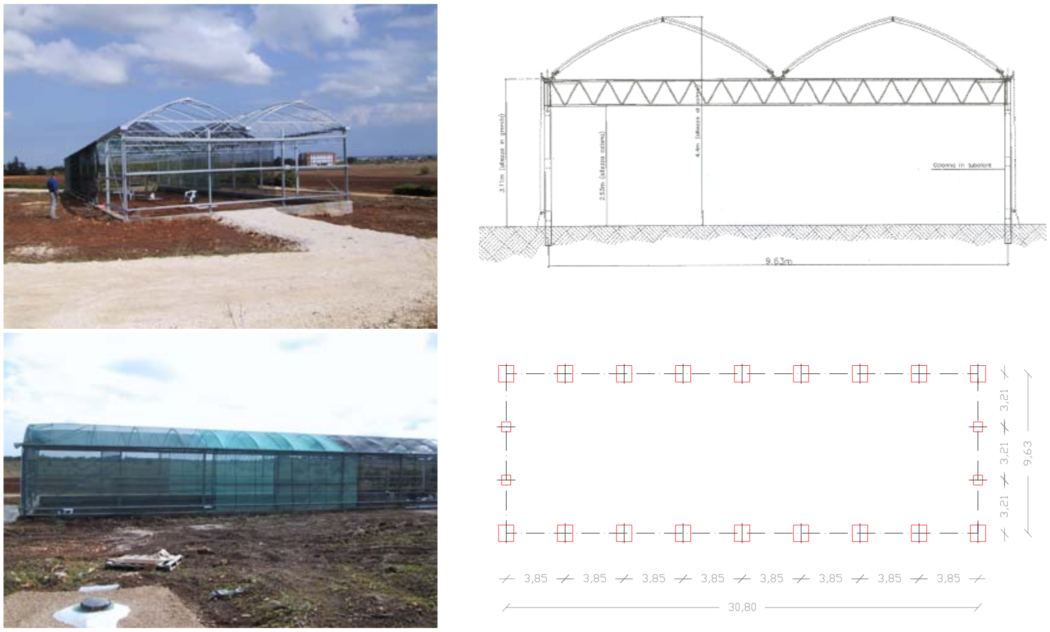


Figure 2 Full- scale net covered greenhouse construction built in Bari, Italy, to be analysed with the light model RAYPRO

Figure 3 Full- scale screen house built in Bari, Italy, covered with four different kinds of net: Libeccio 60 black/green, Ombraverde 50 green and Scirocco 50 black, Agriombra 50 black.

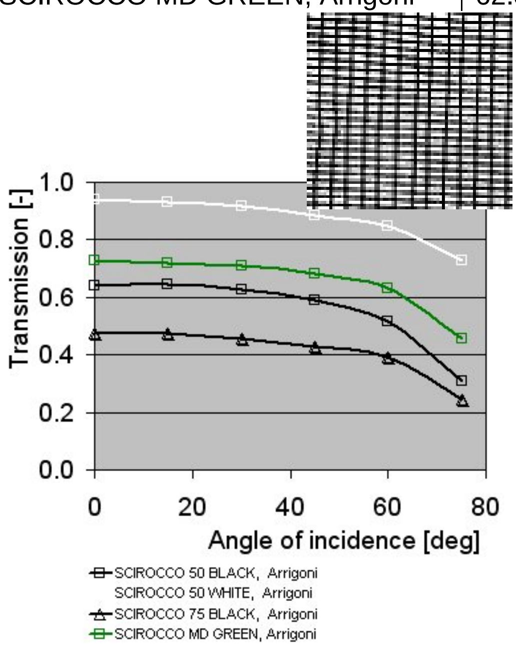
Figure 4 Model of the net covered construction in RAYPRO

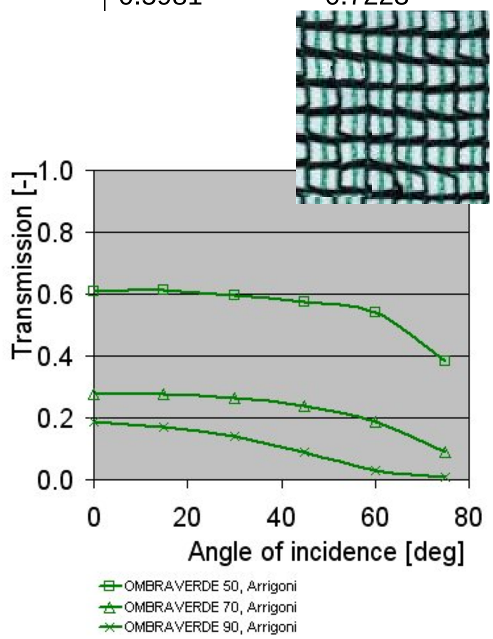
Net properties

Another important input factor of the model are the optical properties of the net, next to the geometry of the net construction. For the analysis of the performance of net and net construction this paper will focus on four different groups of shading nets: Agriombra, Scirocco, Libeccio and Ombraverde, all produced by Arrigoni, Italy. Within the four different groups several nets are analysed. The optical properties of those nets are summarised in Table 2 and Figure 5. A special focus is laid on the four nets used in the screen house in Bari: Libeccio 60 black/green, Ombraverde 50 green and Scirocco 50 black, Agriombra 50 black (Table 3, Figure 6). All those nets have different characteristics. The transmission for diffuse light and for direct light often differ, because of the three dimensional properties of the nets. For example Agriombra 50 and Libeccio 60 show the same transmission for diffuse light, but Libeccio shows a 8% higher transmission for direct light (Table 3). On the other hand Ombraverde 50 has a 2% lower transmission for direct light compared to Scirocco 50, but a 3% higher transmission for diffuse light (Table 3). The transmission of the nets under different angles of incidence is given in Figure 5. An angle of 0 degree is light falling perpendicular on the net surface, an angle of 90 degree is light falling parallel on the net surface. The figures show that Ombraverde and Agriombra nets show a relatively higher transmission when light is falling on the nets with high angles of incidence (Figure 6). Overall it can be concluded that the nets within the group of Ombraverde and Agriombra have a relatively good transmission for diffuse light, whereas the nets belonging to the group of Libeccio and Scirocco show a relatively bad transmission for diffuse light. It can be expected that Ombraverde and Agriombra give relatively more light on cloudy days, when light is especially important.

Table 2 Transmission direct and diffuse of four groups of shading nets to be analysed with the light model RAYPRO

Product	**Porosity**	**Transmission diffuse**	**Transmission direct**
AGRIOMBRA 30 BLACK, Arrigoni	45.3	0.4885	0.5591
AGRIOMBRA 50 BLACK, Arrigoni	47.9	0.4286	0.5094
AGRIOMBRA EXTRA WHITE, Arrigoni	4.4	0.4011	0.4661
OMBRAVERDE 50, Arrigoni	54.4	0.5274	0.614
OMBRAVERDE 70, Arrigoni	21.3	0.2032	0.2676
OMBRAVERDE 90, Arrigoni	12.5	0.1136	0.1784
LIBECCIO 30, Arrigoni	71.2	0.6928	0.796
LIBECCIO 50, Arrigoni	54.4	0.4947	0.6518
LIBECCIO 60, Arrigoni	44.9	0.426	0.5828
LIBECCIO 70, Arrigoni	29.1	0.3168	0.4773
SCIROCCO 50 BLACK, Arrigoni	62.1	0.4984	0.6343
SCIROCCO 50 WHITE, Arrigoni	61.7	0.8628	0.9415
SCIROCCO 75 BLACK, Arrigoni	38.3	0.3306	0.4619
SCIROCCO MD GREEN, Arrigoni	62.3	0.5981	0.7223





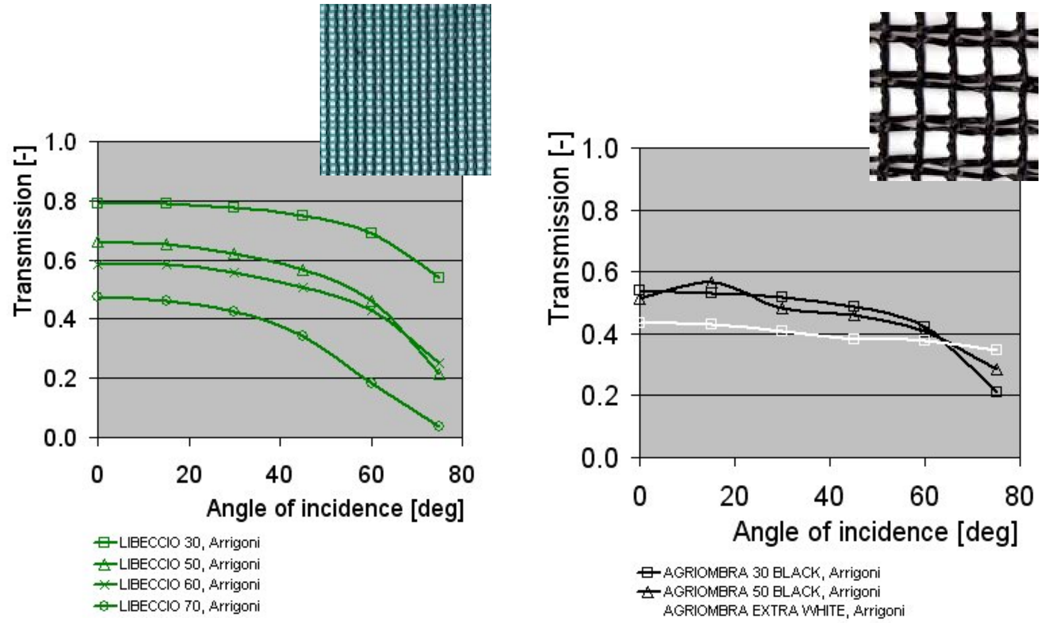


Figure 5 Transmission under different angles of incidence of four groups of shading nets to be analysed with the light model RAYPRO

Table 3 Transmission direct and diffuse of four shading nets

Net	Porosity	Transmission direct	Transmission diffuse
Scirocco 50 black	62.1	63.4	49.8
Ombraverde 50 black-green	54.4	61.4	52.7
Libeccio 60 black-green	44.9	58.3	42.6
Agriombra 50 black	47.9	50.9	42.8

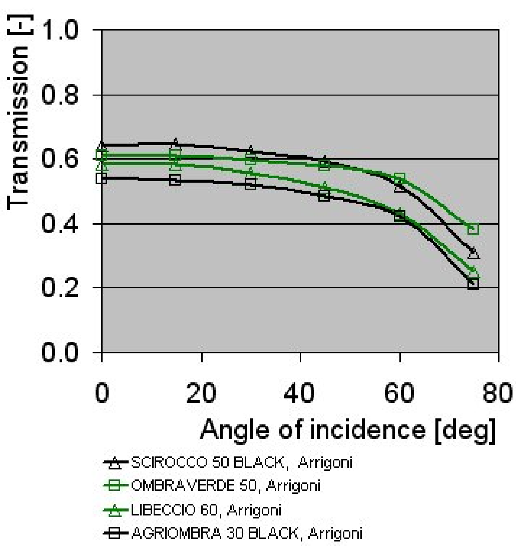


Figure 6 Transmission under different angles of incidence of four shading nets

Calculations with RAYPRO

With the above described input parameters the amount of light inside a given net construction, covered with a given type of nets, located at a given location with a given outside radiation, can be calculated for every hour of the year. This calculation is done separately for the amount of diffuse and for direct light, expressed as the amount of PAR (400-700nm), relevant for plant growth. If PAR diffuse and PAR direct are added the total amount of PAR for the crop results.

The model RAYPRO was used to analyse the light level year-round under four different net types on a net construction in Bari. Model calculations and measurements were compared.

Measurements in a screen house

In order to evaluate the model calculations, in situ light transmission measurements are carried out in the screen house in Bari, Italy. Open field radiometric test were performed by means of a portable spectroradiometer GER 2600 used inside and outside the screen house. The acquisition range was 250-2500nm. The ratio between the measurements obtained inside the screen house and the solar radiation defines the transmissivity of the material. The measurement setup is shown in Figure 7.

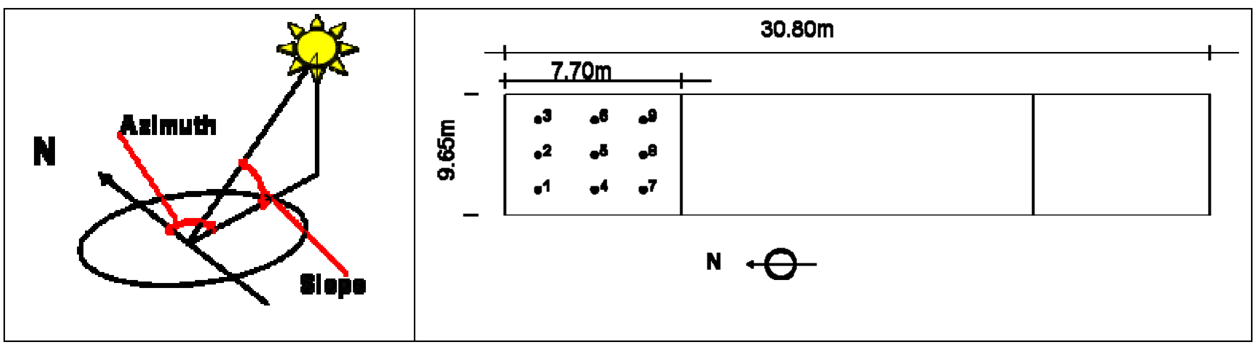


Figure 7 Measured light transmission in the screen house located at Bari, Italy. Sun position (azimuth and slope angles) (left), different measurement points on the floor in one of the greenhouse compartments (right).

Results and Discussion

The light level under four groups of shading nets is analysed with the new developed light model RAYPRO. Each group of shading nets consisted of different nets having a different porosity, sometimes having different colours (Figure 5). The texture of the net groups differed, while Agriombra, Ombraverde en Libeccio were knitted nets, Scirocco had a woven texture.

The year-round performance of the four groups of nets is shown in Table 4 to Table 7. From the net properties, determined in the lab is can be expected that Scirocco 50 White gives the highest light level and Ombraverde 90 gives the lowest light level year-round. Indeed, this result is also found by the model calculations (Table 7 and Table 4). It can further be expected that the colour of the net has an important influence on the light level inside the net covered construction. This can also be confirmed by the model calculations. The white net of Scirocco 50 transmits more PAR than the black net with the same texture and porosity (Table 2 and Table 7). Moreover, we can conclude that a net with the same texture and the same colour but a decreasing porosity, will have a reduced light transmission and a reduced light level throughout the year. This can be shown on the example of the nets within the Ombraverde group (Table 2 and Figure 8) or within the Libeccio group (Table 2 and Figure 9).

Next to the year-round performance of the nets, it is interesting to analyse differences between nets during different seasons (winter, summer) and differences between cloudy and clear sky conditions. On cloudy days with low light intensities, like the 1st of February, the light level inside the greenhouse is determined by the diffuse transmission factor of the selected net. Ombraverde 50 shows the best performance, since it has the highest transmission factor for diffuse light (Figure 12 left). On a cloudy summer day, like the 11th of August, the diffuse light transmission of the net is again the major factor for the light level inside the greenhouse, but not the only one. Also on a relatively cloudy day about one third of the radiation in Bari is still direct. Therefore, the direct transmission factor of the net has still a small influence. Ombraverde 50 still shows the best performance, though (Figure 13 left). In general differences in diffuse light transmission of the nets determine the performance of the net covered structure in practice on cloudy days.

On clear days the amount of direct light is increasing. However, also on those days the amount of diffuse light is still an important factor, especially in winter. On clear days in winter, like the 22nd of February, half of the radiation is direct, half of it is diffuse. Both, the direct and the diffuse transmission factor of the net determine the light level inside the net covered structure. Since Scirocco 50 has the highest direct transmission, most light will reach the crops under Scirocco 50 (Figure 12). On clear summer days with a high amount of direct light, like the 2nd of August, the effect of the direct transmission factor of a net is obvious. Scirocco 50 gives most light to the crop (Figure 13). In general on clear days the direct transmission factor of a net for different angles of incident is important. Since part of the global radiation is always diffuse, the diffuse transmission factor plays a role, too, to determine the light level in a screen house in practice.

Since both transmission factors play a role to determine the performance of a net covered structure in practice, a more detailed analysis is necessary. In this analysis it is examined what happens year-round, when a net has a higher direct transmission but a lower diffuse transmission compared to another net with the opposite properties, and in which times of the year such a net gives a higher and when a lower transmission. The analysis is done on two nets, Ombraverde 50 black and Scirocco 50 black-green.

Comparing Ombraverde 50 and Scirocco 50, it can be noticed that Ombraverde 50 has a 4% lower direct transmission than Libeccio 50, while the diffuse transmission is 3% higher (Table 2). The total light sum under Ombraverde 50 during summer months is about 350 MJ/m^2, in the winter months it is about 80 MJ/m^2 (Table 4 and Figure 8). The total light sum under Scirocco 50 during summer months is slightly higher, during winter months it is comparable (Table 7 and Figure 11). Year-round the total light sum under Scirocco 50 is slightly higher than under Ombraverde 50. From Figure 14 it can be seen, when those difference between Scirocco 50 and Ombraverde 50 occur during the year. Due to the higher direct transmission of Scirocco 50, the light level under that net is during most times of the year higher than under Ombraverde 50, especially during summer months. However, the same Figure 14 shows that also during the summer the use of Ombraverde 50 is during several time periods is advantageous for the crops. Especially during morning and evening hours Ombraverde 50 is advantageous (Figure 15). Here the better transmission of Ombraverde under high angles of incidence seems to be positive. The same is true for diffuse days. That means that during time periods, when light is in minimum Ombraverde 50 gives relatively more light to the crops. In general a net with a high transmission factor for diffuse light and a high transmission under high angles of incidence is preferable for the crops.

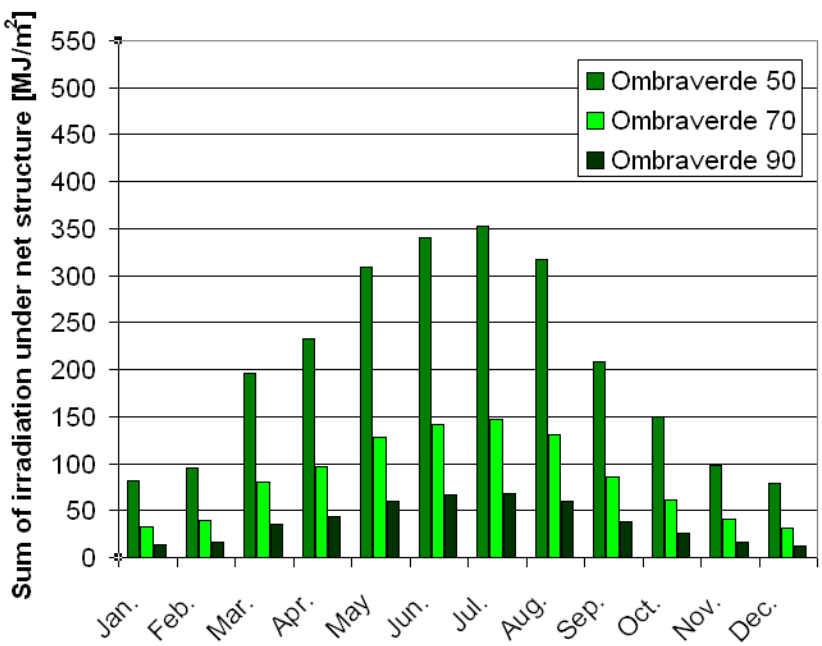


Figure 8 Light level under Ombraverde nets, calculated with RAYPRO

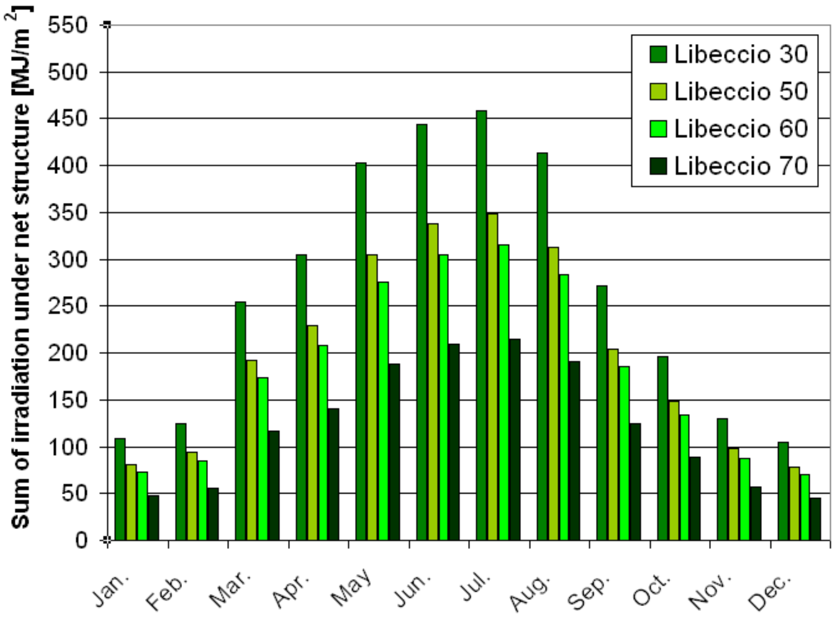


Figure 9 Light level under Libeccio nets, calculated with RAYPRO

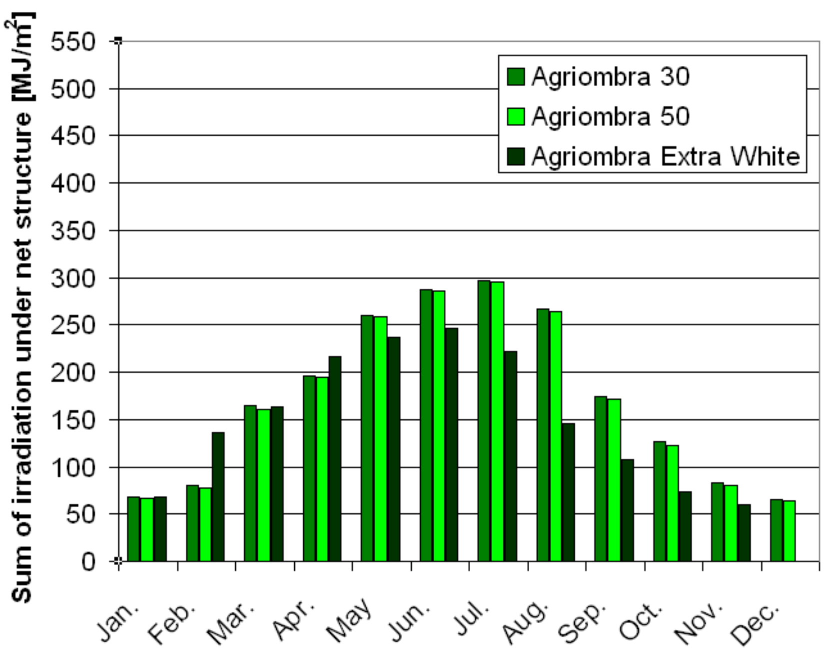


Figure 10 Light level under Agriombra nets, calculated with RAYPRO

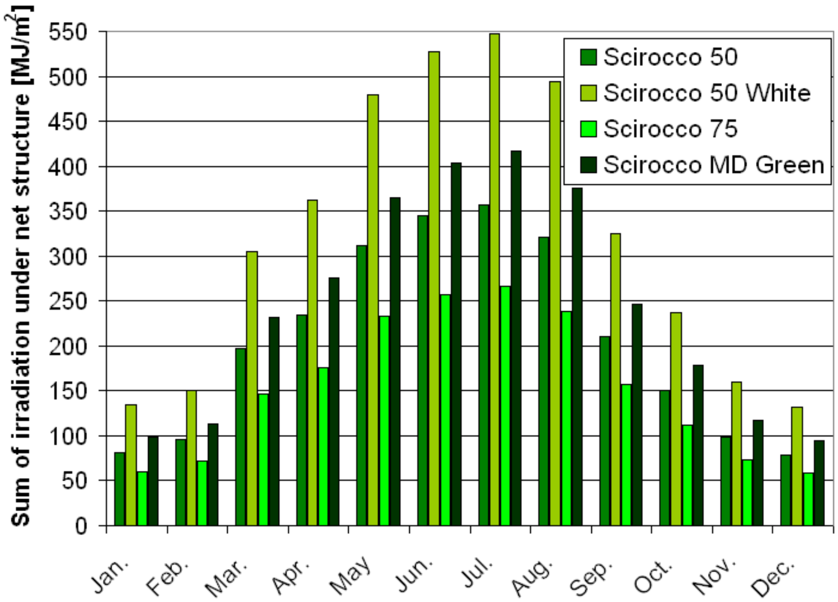


Figure 11 Light level under Scirocco nets, calculated with RAYPRO

Table 4 Total, direct and diffuse PAR under Ombraverde nets, calculated with RAYPRO

	Ombraverde								
	50	70	90	50	70	90	50	70	90
	Total PAR			Direct PAR			Diffuse PAR		
Month	**in MJ/m²**	**in MJ/m**	**in MJ/m²**	**in MJ/m²**	**in MJ/m²**	**in MJ/m²**	**in MJ/m²**	**in MJ/m²**	**in MJ/m²**
Jan.	81.6	33.3	13.4	29.4	11.8	4.0	52.2	21.4	9.4
Feb.	95.4	39.2	16.3	45.4	18.7	7.4	49.9	20.5	8.9
Mar.	195.4	80.6	35.3	115.5	47.7	21.0	79.9	32.8	14.3
Apr.	233.3	96.6	44.2	134.7	56.0	26.6	98.6	40.5	17.7
May	308.8	128.3	59.2	172.1	72.1	34.7	136.8	56.2	24.5
Jun.	340.4	142.0	66.4	203.6	85.8	41.9	136.8	56.2	24.5
Jul.	352.4	146.6	68.1	216.7	90.8	43.8	135.8	55.8	24.3
Aug.	317.4	131.2	60.3	203.7	84.5	39.9	113.7	46.7	20.4
Sep.	208.5	85.9	38.2	122.4	50.4	22.8	86.1	35.4	15.4
Oct.	150.4	61.6	25.7	77.0	31.5	12.6	73.4	30.1	13.1
Nov.	98.5	40.2	16.2	40.1	16.2	5.7	58.4	24.0	10.5
Dec.	78.7	32.0	12.9	23.5	9.2	3.0	55.2	22.7	9.9
Total	**2460.8**	**1017.3**	**456.2**	**1384.1**	**574.8**	**263.5**	**1076.8**	**442.4**	**192.7**

Table 5 Total, direct and diffuse PAR under Libeccio nets, calculated with RAYPRO

	Libeccio											
	30	50	60	70	30	50	60	70	30	50	60	70
	Total PAR				Direct PAR				Diffuse PAR			
Month	**in MJ/m²**	**in MJ/m**	**in MJ/m²**	**in MJ/m²**	**in MJ/m²**	**in MJ/m²**	**in MJ/m²**	**in MJ/m²**	**in MJ/m²**	**in MJ/m**	**in MJ/m²**	**in MJ/m²**
Jan.	108.3	81.2	73.0	47.3	40.1	30.0	26.6	16.3	68.1	51.2	46.4	30.9
Feb.	124.6	94.2	85.0	56.3	59.5	45.1	40.6	26.7	65.2	49.0	44.4	29.6
Mar.	254.9	192.2	174.0	117.0	150.5	113.7	103.0	69.6	104.4	78.5	71.1	47.3
Apr.	304.2	229.8	208.2	141.0	175.5	132.9	120.5	82.5	128.7	96.8	87.7	58.4
May	402.5	305.2	276.3	187.8	223.9	170.9	154.6	106.8	178.7	134.4	121.7	81.0
Jun.	443.4	337.8	305.3	209.2	264.9	203.5	183.7	128.2	178.6	134.3	121.6	81.0
Jul.	459.2	348.8	315.6	215.2	281.9	215.5	194.8	134.8	177.3	133.4	120.8	80.4
Aug.	413.8	312.2	283.1	191.1	265.3	200.5	181.9	123.8	148.5	111.7	101.2	67.4
Sep.	272.1	204.6	185.5	124.6	159.7	120.0	108.9	73.6	112.4	84.5	76.6	51.1
Oct.	196.4	147.9	133.6	88.2	100.6	75.8	68.4	44.8	95.8	72.0	65.3	43.4
Nov.	129.9	97.7	87.9	57.1	53.7	40.3	35.9	22.5	76.3	57.4	52.0	34.6
Dec.	105.2	78.6	70.5	45.5	33.0	24.3	21.3	12.7	72.1	54.2	49.1	32.8
Total	**3214.6**	**2430.2**	**2197.9**	**1480.3**	**1808.5**	**1372.8**	**1240.3**	**842.3**	**1406.2**	**1057.5**	**957.7**	**637.9**

Table 6 Total, direct and diffuse PAR under Agriombra nets, calculated with RAYPRO

	Agriombra								
	30	50	Extra White	30	50	Extra White	30	50	Extra White
	Total PAR			Direct PAR			Diffuse PAR		
Month	**in MJ/m^2**	**in MJ/m**	**in MJ/m^2**	**in MJ/m^2**	**in MJ/m^2**	**in MJ/m^2**	**in MJ/m^2**	**in MJ/m^2**	**in MJ/m^2**
Jan.	68.3	66.2	61.5	24.5	23.3	24.7	43.7	42.9	36.8
Feb.	80.1	77.6	68.1	38.3	36.5	32.9	41.8	41.1	35.2
Mar.	164.2	160.2	136.8	97.2	94.5	80.5	67.0	65.7	56.3
Apr.	196.1	194.0	163.1	113.5	112.9	93.6	82.6	81.1	69.5
May	260.1	258.1	215.9	145.5	145.6	119.5	114.6	112.5	96.4
Jun.	287.4	285.7	237.3	172.8	173.2	140.9	114.6	112.5	96.4
Jul.	297.1	295.3	246.1	183.3	183.7	150.4	113.8	111.6	95.7
Aug.	266.5	264.5	222.1	171.2	171.0	142.0	95.3	93.5	80.1
Sep.	174.9	171.7	146.1	102.7	100.9	85.3	72.2	70.8	60.7
Oct.	126.1	122.2	107.0	64.7	61.9	55.3	61.5	60.3	51.7
Nov.	82.5	79.8	73.1	33.5	31.7	31.9	49.0	48.0	41.2
Dec.	65.6	63.9	60.5	19.3	18.5	21.5	46.3	45.4	38.9
Total	**2069.0**	**2039.3**	**1737.5**	**1166.6**	**1153.8**	**978.4**	**902.4**	**885.5**	**759.0**

Table 7 Total, direct and diffuse PAR under Scirocco nets, calculated with RAYPRO

	Scirocco											
	50	50 White	75	MD Green	50	50 White	75	MD Green	50	50 White	75	MD Green
	Total PAR				Direct PAR				Diffuse PAR			
Month	**in MJ/m^2**	**in MJ/m**	**in MJ/m^2**	**in MJ/m^2**	**in MJ/m^2**	**in MJ/m^2**	**in MJ/m^2**	**in MJ/m^2**	**in MJ/m^2**	**in MJ/m**	**in MJ/m^2**	**in MJ/m^2**
Jan.	81.5	134.1	60.5	97.9	30.2	52.3	21.4	36.0	51.2	81.7	39.1	61.9
Feb.	95.7	150.5	71.4	113.3	46.6	72.3	33.9	54.1	49.0	78.2	37.5	59.2
Mar.	197.0	304.7	146.7	231.5	118.4	179.5	86.8	136.8	78.5	125.2	60.0	94.8
Apr.	235.0	362.9	175.6	276.1	138.2	208.4	101.7	159.3	96.8	154.4	74.0	116.9
May	311.3	479.9	232.8	365.5	176.9	265.7	130.2	203.4	134.4	214.3	102.6	162.1
Jun.	344.3	527.9	257.1	402.9	209.9	313.7	154.4	240.7	134.3	214.2	102.6	162.1
Jul.	356.3	547.1	265.9	417.1	222.9	334.4	164.1	256.1	133.4	212.7	101.8	161.0
Aug.	320.3	493.6	239.0	375.6	208.6	315.5	153.7	240.8	111.7	178.1	85.3	134.8
Sep.	209.8	325.1	156.6	247.0	125.3	190.2	92.0	145.0	84.5	134.8	64.6	102.0
Oct.	150.8	236.7	112.5	178.4	78.8	121.9	57.5	91.5	72.0	114.9	55.0	86.9
Nov.	98.5	159.8	73.2	117.7	41.1	68.4	29.4	48.5	57.4	91.5	43.8	69.2
Dec.	78.4	131.3	58.1	94.7	24.1	44.8	16.6	29.3	54.2	86.5	41.5	65.5
Total	**2478.7**	**3853.6**	**1849.4**	**2917.8**	**1421.2**	**2167.2**	**1041.7**	**1641.4**	**1057.5**	**1686.4**	**807.7**	**1276.3**

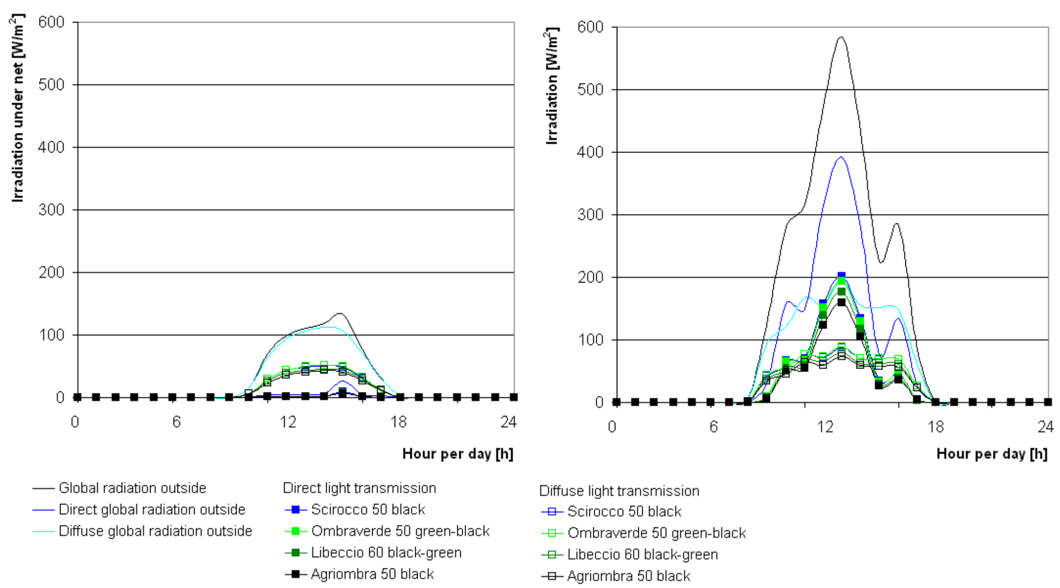


Figure 12 Light level on two selected winter days: 1st of February, cloudy day (left), and 22nd of February, clear day (right).

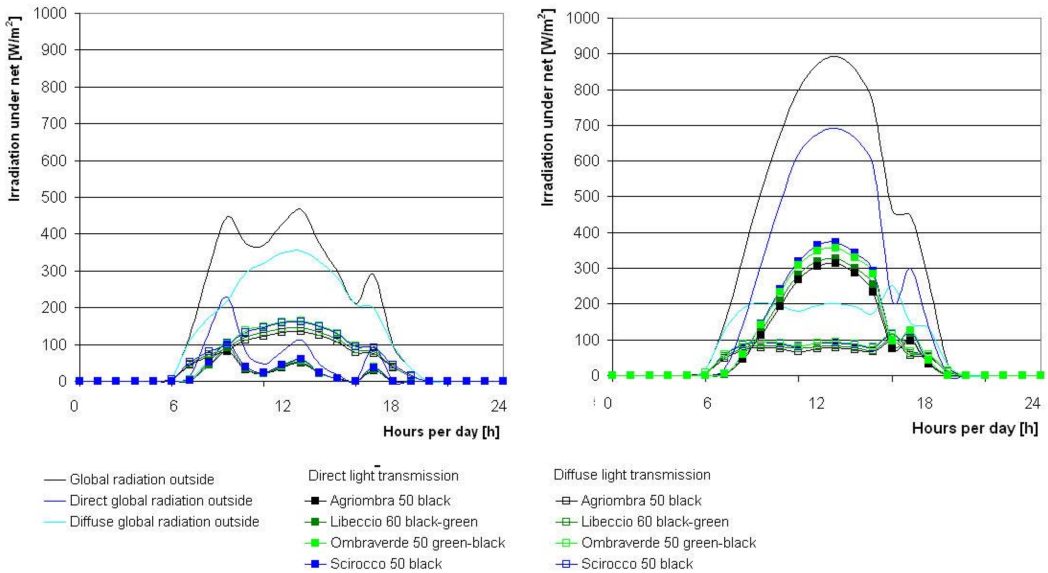


Figure 13 Light level on two selected summer days: 11th of August, cloudy day (left), and 2nd of August, clear day (right).

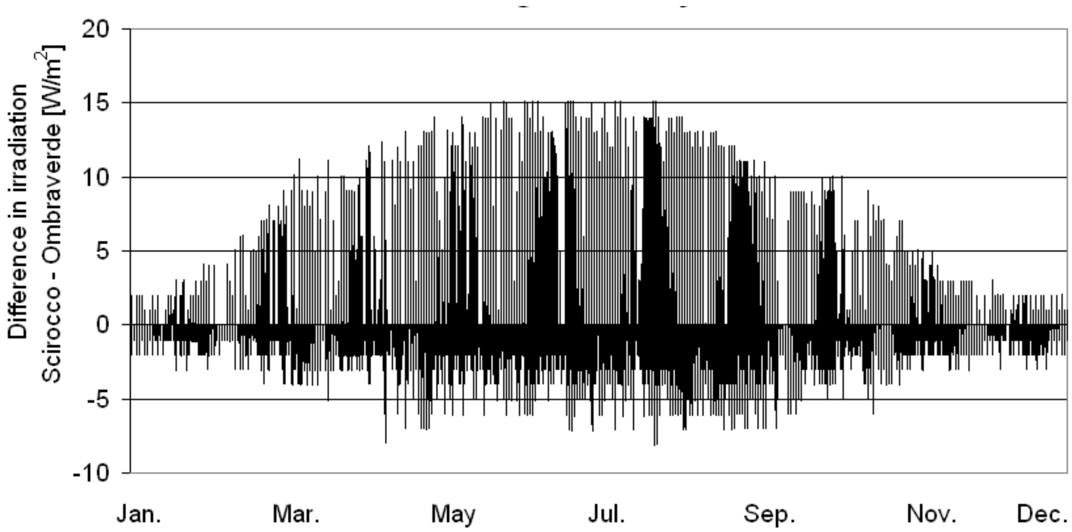


Figure 14 Difference between the light level inside a construction covered with Scirocco 50 or Ombraverde 50 year-round. Positive points represent a higher light level under Scirocco 50, negative points represent a higher light level under Ombraverde 50.

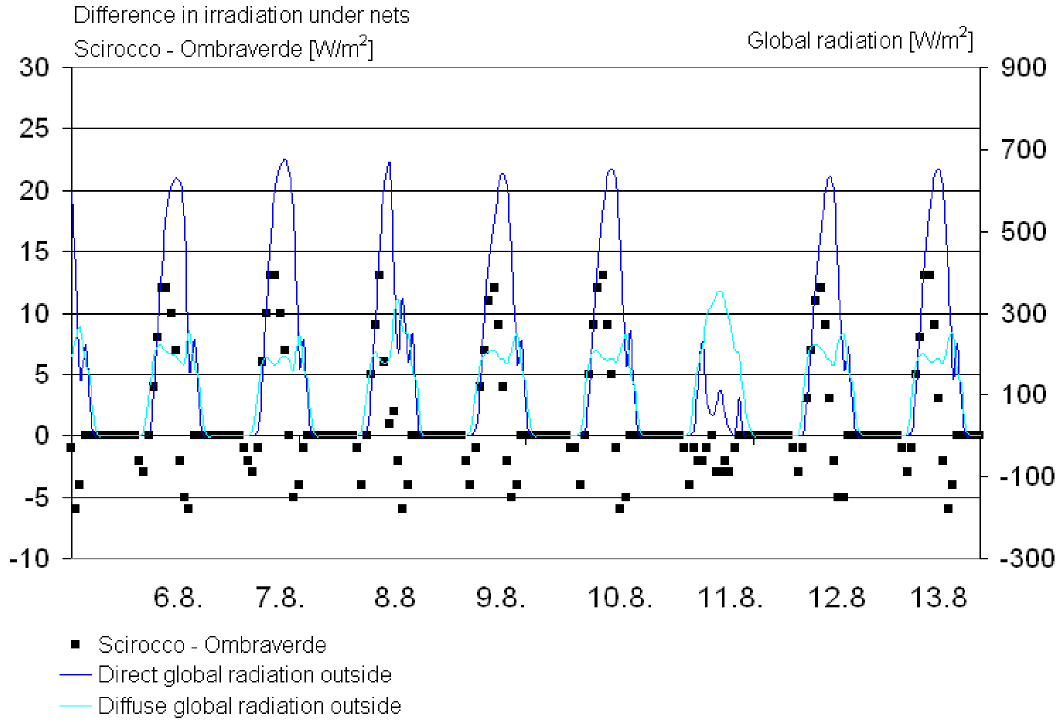


Figure 15 Difference between the light level inside a construction covered with Scirocco 50 or Ombraverde 50 during selected days during summer months. Positive points represent a higher light level under Scirocco 50, negative points represent a higher light level under Ombraverde 50.

For evaluation purposes of the new developed light model in situ-measurements have been carried out by the University of Bari on an identical screen house located at the experimental station at Bari. The results of the first measurement series on nine different points within the Libeccio 60 compartment are shown in Figure 16, the azimuth and elevation of the sun are given as well as the orientation of the screen house. A large variation in light transmittance can be observed due to the different positions in the screen house. The mean value of transmittance measurements were low, about 30%. Especially the positions close to the sidewalls show lower transmittance values. The values recorded show that net transmittance was noticeably reduced inside the screen house and that the supporting structure caused a modification of the light spectrum. Since the measurements were carried out during winter-time with a relatively low elevation of the sun, we cannot exclude the possibility that the measurements were influenced by other compartments of the screen house, which are south of the investigated compartment, and by strong side-wall effects. However, model calculations for the same period of the year, the same location and the same screen house geometry covered with a Libeccio 60 green-black net give transmission values of 33-44% at noon.

The results of the second measurement series in the middle of the different compartment of the screen house covered with Libeccio 60 black-green, Scirocco 50 black, Ombraverde 50 green and Agriombra 50 black are given in Figure 17, the elevation of the azimuth and elevation of the sun are given. The compartment covered with Scirocco 50 shows the highest transmittance, followed by Ombraverde 50 and Libeccio 60. Agriombra 50 has the lowest transmittance. This order can also be expected from the measured optical properties of the nets and from the light model calculations. The highest light level under Scirocco 50 on a sunny day is also estimated by the new developed light model, though the measured values are somewhat higher than predicted. While the measured values of the PAR transmittance are between 55% and 57% for the compartments covered with Ombraverde 50, Libeccio 60 and Agriombra 50, the model estimated those values to be between 46 and 52% during that time of the year at noon. A higher value of the field measurements can be explained by the fact that measurements were only carried out in the middel of the compartment and side-wall effects are not taken into account, while the model calculates a mean value for the whole compartment. The measured transmittance value of Scirocco 50 compartment, though, seems to be relatively high compared with the other three compartments (Figure 17). If we additionally consider the results of the optical properties of the single nets in the laboratories (Table 3), we have to conclude that the measurement of the transmittance of the screen house covered with Scirocco 50 may probably be overestimated.

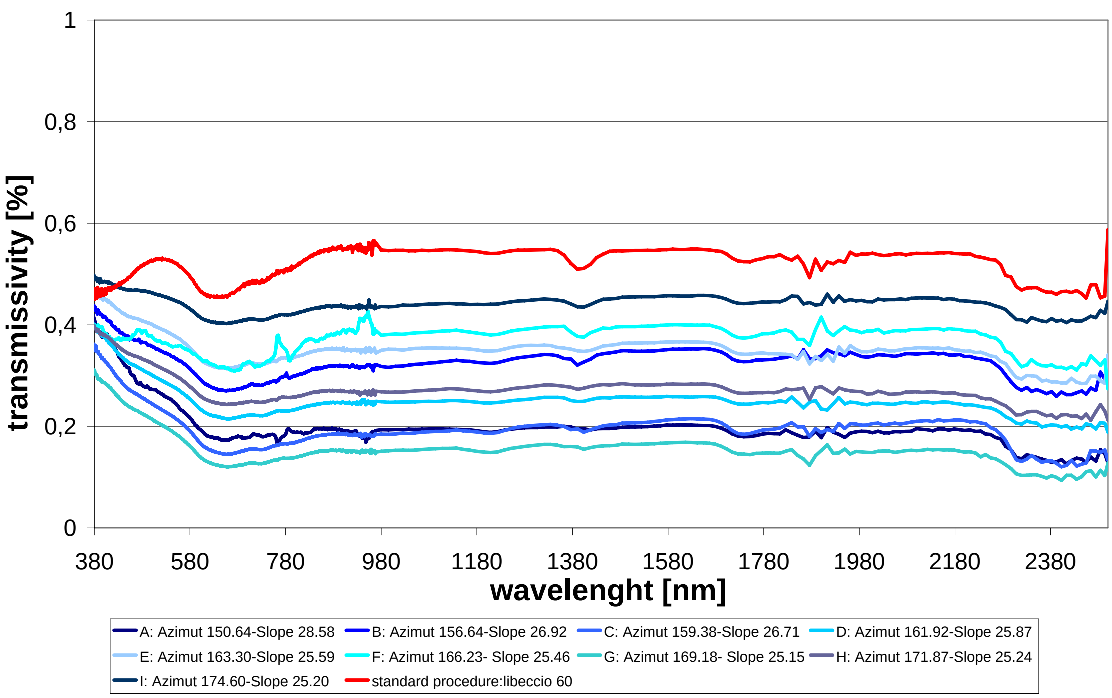
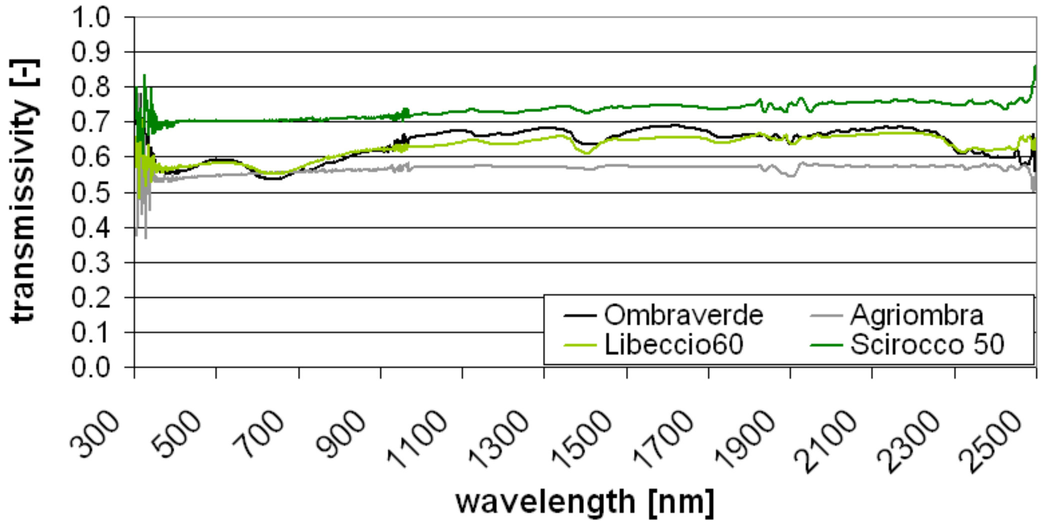


Figure 16 Transmittance of the screenhouse covered with Libeccio 60 black-green situated in Bari, Italy, measured on a sunny winter day at 9 points in that compartment.



	Date	Time	Position sun (azimuth)	Slope sun (elevation)
Agriombra	21-9-2006	10.55	144	43.27
Scirocco	21-9-2006	11.35	159	46.15
Ombraverde	21-9-2006	11.55	166	46.27
Libeccio	21-9-2006	12.10	170	47.37

Figure 17 Transmittance of the screenhouse covered with four different nets (Libeccio 60 black-green, Scirocco 50 black, Ombraverde 50 green and Agriombra 50 black) situated at Bari, Italy, measured on a sunny autumn day in the middle of each compartment.

Conclusion

The design of structures to support nets for agricultural applications is mostly empirical. The radiometric behaviour of a net covered structure strongly depends on the external light conditions and on the net properties. Nets are three-dimensional objects, which optical properties can be different for different angles of incidence in the case of a clear sky (transmission for direct light) and they may show a different transmission for overcast sky conditions (transmission for diffuse light).

For these reasons, a light model (RAYPRO) based on the ray-tracing method is developed by Wageningen UR Greenhouse Horticulture to be able to analyse the radiometric performance of a structure covered with nets. The objectives of the use of a light model were:

- Estimating the year-round light interval of a net structure on plant level

- Analysing the optical properties of different net structures during different seasons and different times of the day.
- Developing a simple method to estimate the optical properties of a net structure relevant for plant growth, use that as a tool for producers and growers

Input parameters of the light model are:

- Latitude, longitude, hour of day, elevation of the sun, azimuth of sun
- Outside radiation: quantity of direct and diffuse radiation
- Geometry and orientation of the structure, azimuth of the roof
- Geometry and position of construction elements
- Radiometric properties of the nets as measured in the laboratories

The performance of four groups of shading nets is analysed with the new developed light model RAYPRO. Calculations are done for a screen house built in Bari. In situ measurements in that screen house are used to evaluate the model. The following conclusions can be given:

- The colour of the net has an important influence on the light level inside the net covered construction. Example: A screen house covered with the white net of Scirocco 50 transmits more PAR than the black net with the same texture and porosity.
- A net with the same texture and the same colour but lower porosity, will have a reduced light transmission and will result in a reduced light level throughout the year. Example: A screen house covered with nets from the Ombraverde or Libeccio group show a decreasing light transmission with decreasing porosity.
- The transmission factor of a net for diffuse light determines the performance of the net covered structure in practice on cloudy days, especially during winter months.
- On clear days the transmission factor of a net for direct light under different angles of incident is important. Since part of the global radiation is always diffuse (also on a clear day), the diffuse transmission factor plays a role, too, in the determination of the light level in a screen house in practice.
- A net with a high transmission factor for diffuse light and a high transmission under high angles of incidence is preferable for crops, since it gives more light during periods when light is in the minimum and can be used by the crops.

- Grower should chose a net with the right shading factor fitting best by the needs of his crops. Nets with the same shading factor but a higher transmission for diffuse light are preferable.
- The light transmission model gives a good estimation of the light levels on crop height in practice and is useful as a design tool for net covered greenhouse structures. It can also be developed further as a decision support tool for growers.

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