J. of Ag. Eng. - Riv. di Ing. Agr. (2010), **2**, 1-12

RADIOMETRIC PROPERTIES OF AGRICULTURAL PERMEABLE COVERINGS

Sergio Castellano, Silke Hemming, Giovanni Russo, Vida Mohammadkhani, Gert-Jan Glam Swinkels, Giacomo Scarascia-Mugnozza

1. Introduction

A large number of net types for agricultural applications with different construction characteristics exist in the market. Nets can be classified by the kind of threads, fabrics, dimensions of fibres and meshing, weight, colours, shading factor, durability, porosity, air permeability, breaking strength and elongation. Main agricultural applications are: protection against meteorological hazards, insects, small animals; reduction of solar radiation; soil cloth; harvesting; packaging and post-harvesting operations. It is not always possible to associate a net to a specific application, as in many cases they accomplish more functions at the same time, for example, often shading nets protect also cultivation from hail.

While the air flow resistance of different kinds of insect nets is widely investigated [Bailey 2003; Demrati 2001; Fatnassi 2002; Fatnassi 2003; Harmanto 2005; Klose 2004; Miguel 1997; Miguel 1998; Soni 2005; Teitel 1996; Teitel 2007; Valera 2005], only little is known about radiometric properties of recent commercial agricultural nets [Castellano 2008] differently from other greenhouse covering materials, such as plastic films [Hemming 2004; Hemming 2006; Impron 2007; Kittas 1998; Pearson 1995], which are investigated regularly.

The radiometric properties of agricultural nets, such as the transmissivity, the reflectivity, the shading factor, the capability to modify the quality of the radiation passing through the net, influence the quality of the agricultural production and the aesthetic characteristics of the netting system. Research in the last decade focused on coloured nets to influence the morphology of plants [Elad 2007; Oren-Shamir 2001; Shahak 2004a; Shahak 2004b; Shahak 2007], and on the effect of UV-blocking nets on insect behaviour [Antignus 1998; Kumar 2006], however, a characterisation of different types of nets for specific purposes is still lacking. Nets are unlike other three-dimensional covering material structures. The whole construction parameters of the net, combined with the shape of the structure, the position of the sun and the sky conditions affect the radiometric performance of the permeable structure [Castellano 2006; Castellano 2008a; Castellano 2008b]. Nets are non-uniform materials, for this reason, radiometric properties should be studied on large enough samples to avoid any small-size effects.

Photosynthetic Active Radiation (PAR, 400-700 nm) transmittance is the most important radiometric property of covering materials from the agronomic point of view, since PAR is necessary for plant photosynthesis. In the PAR region the transmission of perpendicular light and light under different angles of incidence with reference to the net surface is important to characterise the material behaviour on clear days, whereas the transmission for diffuse light characterises the material behaviour on cloudy days. The radiation range from 300 nm to 800 nm is important for plant growth, mostly for morphogenetic responses. This radiation is therefore called Morphogenetic Active Radiation (MAR) by some authors [Varlet-Grancher 1995]. The total solar transmission (300-2500 nm) of materials is important to quantify the amount of energy entering the net structure, which has an important influence on the microclimate inside the screen house. Whereas in non-permeable structures (e.g. plastic film greenhouses) also the transmission for heat radiation (>2.5 μm) is considered to play a major role, it will be less important for open net structures, where convective heat exchanges are more important than radiative heat exchanges. The haze is the percentage of the transmitted direct radiation scattered by a material. Materials with a high haze create an indoor environment with diffuse light, which is preferable for many crops [Hemming 2005; Hemming 2007], particularly in Southern European countries.

Paper received 22.10.2009; accepted 20.08.2010

Sergio Castellano: PRIME Department, University of Foggia, Via Napoli, 25, Italy, e-mail: s.castellano@unifg.it

Silke Hemming, Vida Mohammadkhani, Gert-Jan Glam Swinkels: Wageningen UR, Greenhouse Horticulture, P.O. Box 16, 6700 AA Wageningen, The Netherlands, e-mail: silke.hemming@wur.nl

Giovanni Russo, Giacomo Scarascia-Mugnozza: PROGESA Department, University of Bari, Via Amendola 164, Italy.

Transparent or semitransparent threads may be used for reducing excessive solar radiation and generate mild and more uniform internal light conditions. The colour of the material and the light reflection especially of the wavelengths visible for the human eye (VIS, 380-760 nm) are interesting criteria to determine the aesthetic value of the net structure and the environmental impact. The radiometric behaviour of a net covered structure strongly depends on the external radiative environment. Also the transmittance of the covering system varies with the angle of incidence of the solar radiation in the case of a clear sky. For example, a large angle of incidence combined with a clear sky may create a strong shading effect during daytime, while an overcast sky results in a smaller loss of incoming radiation. The direct light transmittance as a function of the angle of incidence is also an important radiometric property for nets, which is depending on the three-dimensional structure of the material. The light transmittance with respect to a diffuse light source is also investigated since it provides information about the performance of the net under an overcast sky. These properties describe the seasonal and diurnal performance of the material.

In this paper the influence of net construction parameters on their radiometric properties are investigated by means of laboratory and field tests on a large number of commercial net typologies for various functions, such as anti-insect, anti-hail, shading and windbreak nets.

2. Materials and Methods

In order to investigate the influence of net construction parameters on their radiometric properties, a set of laboratory and open field tests were performed on 38 types of high density polyethylene (HDPE) commercial nets and on 7 coloured nets which were made on purpose for this research.

2.1 *Nets tested*

Commercial nets were chosen based on their main agricultural application. Tested nets were characterised by their weight: expressed in g m^{-2}, by their kind of threads: monofilament (M) or tapes (T), by different colours: black (BL), blue (B), green (G), grey (Gy), red (R), transparent (T) white (W) and by their texture: Woven or Italian (I), English woven or Leno (L), Knitted or Raschel (R) (tab. 1, tab. 2, tab. 3, tab. 4).

Anti-hail nets (tab. 1) are largely used in field applications, especially in fruit tree cultivations such as grape, peaches, apricots and cherries, where they are installed with a specific supporting structure or directly applied on the cultivations. They are characterised by meshes as wide as possible in order to improve the ventilation under the net covered area and by transparent yarns or yarns with light colours to reduce the shading effect of the net. This kind of net is characterised by a low deformability and a good mechanical behaviour to resist the impact of hail stones.

ID	Name	Company	Texture[1]	Thread[2]	Colour[3]	Weight
ANTH	ANTI-HAIL NET	Karatzis A.E.	R	T	T	96
GRKR	GRANDILENE KRISTALL	Agrinova	L	M	T	38
IRID	IRIDE UVA	Arrigoni	L	M	T	70
TS065	TS 065-N-NATURAL	Thrace Plast.	R	T	T	65
TS070	TS 070-E	Thrace Plast.	R	T	BL-G	70

[1] Texture: I Italian, L English, R Raschel
[2] Thread: M monofilament, T tape
[3] Colour: black (BL), blue (B), green (G), grey (Gy), red (R), transparent (T) white (W)

TABLE 1 - Anti-hail nets tested, the weight is expressed in [g m^{-2}].

ID	Name	Company	Texture[1]	Thread[2]	Colour[3]	Weight
BIO20A	BIORETE 20/10 (yard 0.23)	Arrigoni	I	M	T	90
BIO20B	BIORETE 20/10 (yard 0.235)	Arrigoni	I	M	T	120
BIO40	BIORETE 40 (MESHES 16/10)	Arrigoni	I	M	T	108
BIO50	BIORETE 50 (MESHES 20/10)	Arrigoni	I	M	T	123
FR2.6T	FRUCTUS 2.6/2.5	Arrigoni	L	M	T	42
FR2.6G	FRUCTUS 2.6/2.5	Arrigoni	L	M	Gy-T	42
FR4.4	FRUCTUS 4/4	Arrigoni	L	M	T	61
IMP	IMPOLLIRETE	Arrigoni	R	M	T	44
INSK	INSECT NET K	Howitec	I	M	T	60
INSM	INSECT NET M	Howitec	I	M	T	90
INST	INSECT NET T	Howitec	I	M	T	130
MAGG	RETE MAGGIOLINI	Arrigoni	L	M	BL	39

[1] Texture: I Italian, L English, R Raschel
[2] Thread: M monofilament, T tape
[3] Colour: black (BL), blue (B), green (G), grey (Gy), red (R), transparent (T) white (W)

TABLE 2 - Anti-insect nets tested, the weight is expressed in [g m^{-2}].

ID	Name	Company	Texture[1]	Thread[2]	Colour[3]	Weight
AGR30	AGRIOMBRA 30	Arrigoni	R	T	BL	53
AGR50	AGRIOMBRA 50	Arrigoni	R	T	BL	67
AGR70	AGRIOMBRA 70	Arrigoni	R	T	BL	87
AGXW	AGRIOMBRA EXTRA WHITE	Arrigoni	R	T	W	95
HEX	HEXAGONAL NET	Howitec	R	M	G	47
OMB50	OMBRAVERDE 50	Arrigoni	R	M, T	G	81
OMB70	OMBRAVERDE 70	Arrigoni	R	M, T	G	99
OMB90	OMBRAVERDE 90	Arrigoni	R	M, T	G	133
SHB	SHADE NET BLUE	Howitec	R	T	B	78
SHR	SHADE NET RED	Howitec	R	T	R	78
SH50	SHADE NET TAPE 50	Howitec	R	T	G	105

[1] Texture: I Italian, L English, R Raschel
[2] Thread: M monofilament, T tape
[3] Colour: black (BL), blue (B), green (G), grey (Gy), red (R), transparent (T) white (W)

TABLE 3 - SShading nets tested, the weight is expressed in [g m^{-2}].

ID	Name	Company	Texture[1]	Thread[2]	Colour[3]	Weight
BRW50	BREAKWIND NET AT 50%	Quartulli	L	M	BL	100
LIB30	LIBECCIO 30	Arrigoni	R	M	BL-G	70
LIB50	LIBECCIO 50	Arrigoni	R	M	BL-G	105
LIB60	LIBECCIO 60	Arrigoni	R	M	BL-G	130
LIB70	LIBECCIO 70	Arrigoni	R	M	BL-G	180
SC50B	SCIROCCO 50 BLACK	Arrigoni	I	M	BL	85
SC50W	SCIROCCO 50 WHITE	Arrigoni	I	M	T	85
SC75B	SCIROCCO 75	Arrigoni	I	M	BL	138
SCMD	SCIROCCO MD GREEN	Arrigoni	I	M	BL-G	72
WBRT	WINDBREAK NET TAPE	Howitec	L	M	BL-G	120

[1] Texture: I Italian, L English, R Raschel
[2] Thread: M monofilament, T tape
[3] Colour: black (BL), blue (B), green (G), grey (Gy), red (R), transparent (T) white (W)

TABLE 4 - Wind-break nets tested, the weight is expressed in [g m^{-2}].

		Laboratory tests					Open field tests		
ID	ϕ	τ_{UV}	$\tau_{PAR\ DIR}$	$\tau_{PAR\ DIFF}$	ρ_{PAR}	σ_{PAR}	τ_{PAR}	τ_{NIR}	τ_S
AGR50	53	50	51	43	1	2	51	52	53
AGXW	4	11	47	40	50	75	43	54	46
ANTH	39	85	89	79	17	28	75	80	77
BIO40	40	75	92	81	15	42	80	85	82
BIO50	34	81	88	77	19	49	78	81	79
BRWT	38	13	54	44	5	16	51	63	55
FR2.6G	82	89	91	85	2	6	87	87	87
FR4.4	78	95	97	91	6	16	94	96	95
HEX	47	66	75	63	6	14	74	83	77
IMP	75	96	97	91	6	15	90	92	91
INSK	69	95	96	89	9	22	91	93	92
INSM	59	95	95	86	11	29	90	93	91
INST	30	89	91	78	18	55	71	73	72
LIB30	71	77	80	69	3	4	75	78	76
LIB50	54	60	65	49	3	18	63	69	65
LIB60	45	53	58	43	3	16	51	56	52
LIB70	29	42	48	32	4	18	41	47	43
OMB50	54	58	61	53	3	8	58	63	60
OMB70	21	26	27	20	4	10	25	33	28
OMB90	13	17	18	11	4	12	16	19	17
SC50B	62	83	63	50	1	2	63	65	64
SC50W	62	64	94	86	11	27	84	86	84
SC75B	38	79	46	33	2	3	39	39	39
SCMD	62	47	72	60	3	7	65	69	66
SH50	40	44	51	38	3	6	49	57	51
TS070	10	47	17	12	3	10	18	26	21

TABLE 5 - Porosity (φ) and radiometric properties (τ_{UV}, $\tau_{PAR\ dir}$, $\tau_{PAR\ diff}$, τ_{NIR}, τ_{sol}, ρ_{PAR}, σ_{PAR}) of tested nets measured in laboratory, with direct and diffuse light source, and in open field. All data are expressed in percentage (%).

		Net sample						
		TT	TB	TLG	TDG	TR	TY	TBL10
Field tests	τ_{TOT}	0,94	0,91	0,90	0,92	0,92	0,92	0,90
Laboratory tests	τ_{DIR}	0,97		0,93	0,95	0,93		0,93
	τ_{DIFF}	0,93		0,87	0,90	0,87		0,87
	ρ	0,050		0,038	0,032	0,039		0,030

TABLE 6 - Transmissivity measured in field (τ_{TOT}), and transmissivity from a direct (τ_{DIR}) and a diffuse (τ_{DIFF}) light source and reflectivity (ρ) measured in the laboratory. Samples made combining in the warp direction transparent threads with transparent (TT), black (TBL), blue (TB), yellow (TY), light green (TLG), dark green (TDG), and red (TR) threads as weft.

Insect nets (tab. 2) are considered as an environmental and human health friendly alternative to some pesticides and are employed in organic farming or in screenhouse coverings, with single or double layers, for virus free production. Insect proof nets are also used to avoid the escape of pollination insects, like bumble bees, from the greenhouse. For this kind of net the size of the mesh is very important, in order to avoid the entrance of insects and virus carriers. Moreover the colour influences the attraction of insects. Insect-proof nets are characterized by a very low porosity which causes a reduction of air flow and an increase of relative humidity, which can be a negative effect for cultivation. To avoid reduction of solar transmittance, transparent fibres are usually used in order to limit the shading effect of the net.

The aim of shading nets (tab. 3) is to screen the solar radiation in order to reduce the air temperature inside greenhouses or the incoming radiation in cultivations, such as ornamental plants, requiring low levels of light. They are used also to prolong or delay the harvesting period in sunny areas. The increasing of the air humidity and the reduction of air flow could be a limiting factor in their use; dark colours, such as green or black, are the most common for this kind of application.

Windbreak nets (tab. 4) are used in order to: avoid mechanical damages (breaking of branches, flowers, etc.) and biological consequences (high evapo-transpiration, difficulties in pollination, etc.) due to the action of the wind on the cultivations; increase the quality of products by protecting them from dust, salt and sand; reduce the wind load on agricultural structures; minimize the heat loss of animals due to ventilation in open livestock farming. The porosity of the net affects the design of the windbreak structure and the performance of the protecting system causing a wind vortex on the leeward side which are potentially dangerous for the cultivation, moreover the shading effect of the windbreak net could cause a decrease of the production.

Finally, a set of seven anti hail nets, based on the Leno fabric [Castellano 2008a], of the commercial type Fructus2.6-2.5, was produced in order to test, in open field, the influence of different colours on the radiometric properties of the net. Samples were made combining in the warp direction transparent threads with transparent (TT), black (TB), blue (TB), yellow (TY), light green (TLG), dark green (TDG), and red (TR) threads as weft (tab. 6).

2.2 *Net porosity*

The porosity (φ), the fraction of the area of voids over the total area of the net, was evaluated by means of the analysis of images of the materials. All tested nets were scanned at the resolution of 2400 dpi. Images were converted into black (threads) and white (empty) with the Adobe Photoshop software. A representative area was selected from each picture and, by means of the same software, the percentage of white pixel of the whole picture was evaluated. Measurements were repeated at least two times for each sample, using areas of different size, and the average value was taken.

2.3 *Laboratory test*

Nets are non homogeneous materials and it is not possible to evaluate radiometric properties by means of laboratory spectrophotometer measurements due to the small dimension of the sample, usually 2-3 cm, and of the light source which is a concentrated ray whose transversal dimension is comparable with the mesh size of the net. For this reason, laboratory tests on large size samples were performed using a large integrating sphere with a radius of 1.00 m and a sample port of 0.40 m diameter and a small integrating sphere with a radius of 0.50 m and a sample port of 0.10m diameter. The total transmissivity in the PAR range (τ_{PAR} in 400-700 nm) of samples with the size of 50 cm by 50 cm was measured with the large integrating sphere, which has a barium sulphate coating inside ($BaSO_4$) (fig. 1).

Data was gathered by means of a diode-array spectrophotometer, with a resolution of 1 nm. A light bundle emitted by halogen lamps perpendicular to the sample was used as a direct light source in order to determine the PAR transmissivity for direct light (τ_{PARdir}) (fig. 1a). The PAR transmissivity for diffuse light ($\tau_{PAR\ diff}$) was determined by using indirect light emitted by fluorescent lamps inside a hemispherical sphere above the integrating sphere (fig. 1b). Moreover, the reflectivity (ρ_{PAR}) in the PAR range was measured in the large integrated sphere.

The total transmissivity in PAR range (τ_{PAR} in 400-700 nm) and in the UV range (τ_{UV} in 300-400 nm) for different angles of incidence (e.g. 0°, 15°, 30°, 45°, 60°, 75°) was measured in the small integrating sphere (fig. 2a) using a xenon lamp as a direct light source in the range of 300-1100 nm range. Also a diode-array spectrophotometer with a resolution of 1nm was used. The size of the samples was 10 cm by 10cm. Moreover, the haze, the percentage of the transmitted radiation scattered by the nets in the PAR range, (σ_{PAR}), was measured by means of the small integrating sphere (fig. 2b).

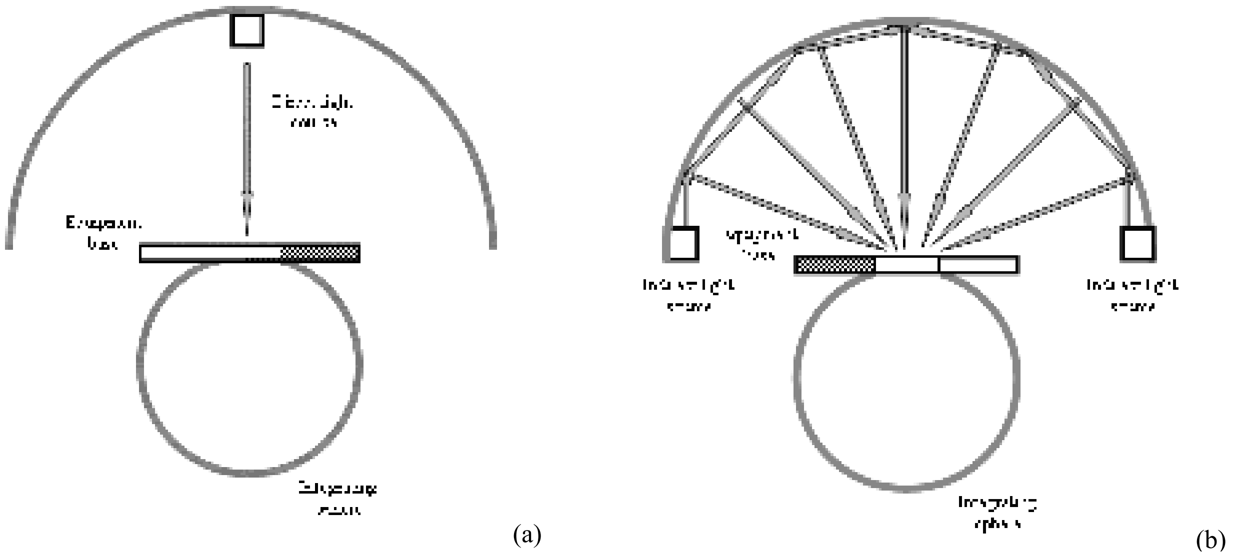

Fig. 1 - Scheme of the laboratory test set-up (large integrating sphere) : measurement of PAR transmission for direct light (a), measurement of PAR transmission for diffuse light (b).

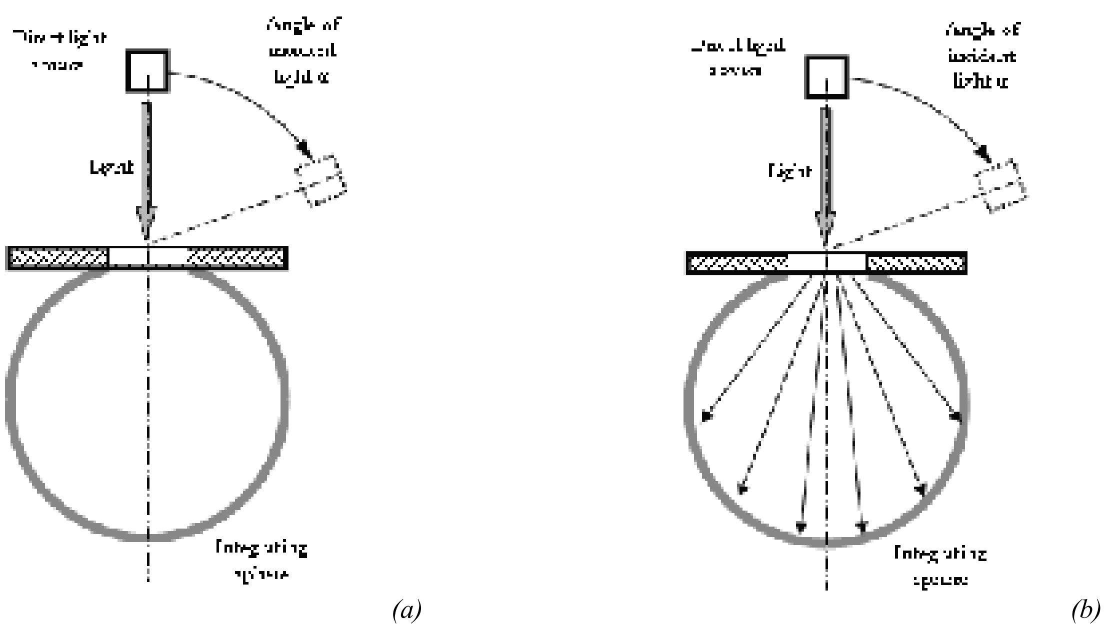

Fig. 2 - Scheme of the Laboratory test set-up (small integrating sphere):, measurement of PAR transmission for direct light under various angles of incident (a), measurement of the haze, scattered light (b).

All laboratory trials were performed at Wageningen UR Greenhouse Horticulture laboratory in The Netherlands.

2.4 *Open field tests*

Open field radiometric test were performed by means of an experimental set up named "*permeable box*" (fig. 3a) and a full scale shade house (fig. 3b) in an experimental field of the University of Bari, in southern Italy (41°02'N, 16°54'E) during the month of September 2005, 2006 and 2007.

The "*permeable box*" consisted of a steel frame 120x120x50 cm whose dimensions were designed in order to avoid the shadow of the frame on the reflective surface of the spectroradiometer. All samples were settled on a square frame 120x120 cm which covered the box and on side walls (480x50 cm) of the box.

The full scale shade house (9.60x30.00x4.40 m) was divided in four different sections, almost 7.00 m long, and covered with four different kinds of shading nets, one for each portion, characterised by about the same shading factor, defined by their technical forms provided by producers, but different colour, kind of threads and fabric (LIB60, OMB50, SC50, AGR50).

In both cases the total solar radiation was measured by means of a portable spectroradiometer_Ger 2600. The acquisition range was 250-2500 nm, and the resolution was 1.5 nm in the wavelength range of 300-

Fig. 3 - Open field test set-up. Permeable box (a) and full scale shade house (b).

1050 nm and 11.5 nm in 1050-2500 nm. Data were gathered by means of a portable computer. The spectroradiometer measured the sun radiation from a very high reflective element coated with $BaSO_4$. The ratio between the measurements obtained under the net sample and outdoor defines the transmissivity of the material (if τ=100% then the material is completely transparent, if τ=0% the material is opaque). That way τ_{PAR} (400-700 nm), τ_{NIR} (780-2500 nm) and τ_{sol} (300-2500 nm) can be determined.

In order to include the spectral distribution of the solar radiation, it is necessary to calculate the weighted average transmittance value over fixed wavelength bands [Scarascia Mugnozza 1998]. In literature [ASTM D1003-07 2007; EN410 1998; ISO 9050 2003; NEN 2675 1990], several weighting functions which describe the spectral distribution at ground level are available. In this research paper, both for laboratory and for open field tests, the NEN2675 was adopted since it has the closest relation with crop photosynthetic reaction and growth.

3. Results and Discussion

3.1 *Radiometric properties in general*

The comparison of the PAR transmissivity in open field (permeable box) and laboratory tests (integrating sphere) show a good accordance of measured values (tab. 5). Laboratory results of $\tau_{PAR,dir}$ are generally higher than open field results, except for TS070 net, depending on the inclination of the sun with respect to the artificial light source which is perpendicular (tab. 5).

For shading nets the light transmission or the shading factor should be one of the most important selection criteria. Since the light transmission differs for different nets it is important to choose the net that fits best with the needs of the crop. It is important to select a net with a high diffuse light transmission $\tau_{PAR,diff}$. For example AGR50 has almost the same shading factor as LIB70 and SC70. AGR50 has a much higher transmission for diffuse light, though. Consequently it protects the crop against extreme light conditions on clear days, whereas it gives relatively more light to the crop on cloudy days, compared to the nets with a lower transmission for diffuse light.

Transmissivity measurements of different nets highlight that the various radiometric ranges do not affect considerably the transmissivity of nets. Measured values in open field tests show very similar values of transmissivity in the solar (τ_{sol} 300-2500 nm), PAR (τ_{PAR} 400-700 nm) and NIR (τ_{NIR} 780-2500 nm) range, which means that all nets are not specially selective for PAR or NIR (tab. 5). However, the UV transmittance of the nets differs due to the presence of different anti-ageing additives, which is highlighted in laboratory test results of τ_{UV} and τ_{PAR}.

Light transmission τ_{PAR} decreases with smaller meshes for woven insect nets. For example BIO40 has a higher transmissivity than BIO50. One exception has to be mentioned. INST has smaller meshes than BIO50, but a higher light transmission due to smaller threads (tab. 5).

Light transmission τ_{PAR} of Italian or English woven nets is in general higher than for knitted nets with the same colour and porosity. BIO40, an anti-insect net with Italian fabric of transparent threads and φ=40%, has a higher transmissivity than ANTH, an anti-hail knitted net with transparent threads and φ=39% (tab. 5).

The reflection ρ_{PAR} of all nets is relatively low. Only the white net AGXW shows a very high reflection, which keeps out the radiation energy and possibly decreases inside air and crop temperatures. The haze σ_{PAR} of the different materials differs slightly. The haze of transparent and white nets is higher than the haze of coloured nets. In general reflection ρ_{PAR} and haze σ_{PAR} increase with smaller meshes and consequently, lower porosity.

Reflectivity, transmissivity and haze and the transmission spectrum are important parameters to know for the design of the nets because the choice of the

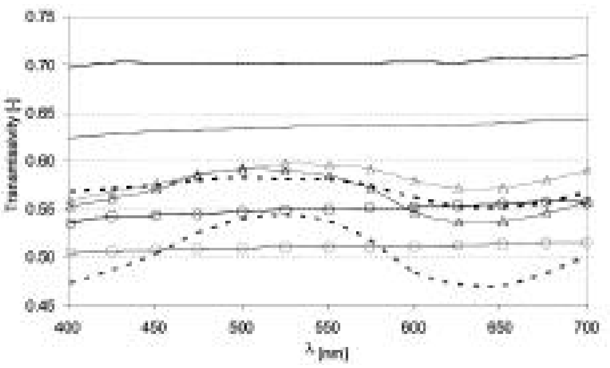

Fig. 4 - Transmissivity in the PAR (400-700nm) range measured for four different nets in the open field shade house- SC50B/F-□-, LIB60/F- -, OMB50/F-Δ-, AGR50/F-○- and in the permeable box- SC50B/B-□-, LIB60/B- -, OMB50/B-Δ-, AGR50/B-○-.

yarn type and size can influence the optical properties of the net.

Small differences can be noticed for the transmissivity τ_{PAR} measured in a permeable box with respect to the full scale shade house. In both measurements SC50B, monowire black net, and AGR50, knitted black nets made by tapes, the transmissivity has the same behaviour with a little increasing, almost the 10%, of the transmissivity measured in the full scale shade house, $\tau_{SC50B/F}\cong70\%$ and $\tau_{AGR50/F}\cong55\%$, with respect to that measured in the permeable box, $\tau_{SC50B/B}\cong64\%$ and $\tau_{AGR50/B}\cong51\%$ (fig. 4). The net LIB60, knitted black and green net made by monowire, shows the same tendency with a more smooth curve in the green range in the shade house, $\tau_{LIB60/F}\cong57\%$, with respect to the permeable box, $\tau_{LIB60/B}\cong50\%$, this effect could be induced by the presence of structural elements which reduce the average green component of the coverings. The transmissivity of OMB50, knitted green net made by monowire and tape, is practically the same in both measurements up to 500 nm, afterwards an increasing of the transmissivity in permeable box- $\tau_{OMB50/F}\cong56\%$ and $\tau_{OMB50/B}\cong$ 58% is highlighted.

In all cases differences are quite small and the curves of transmissivity show almost the same behaviour. Different results are due to edge effects caused both by the diffuse component of the radiation passing through the gable walls and from the distance of the net from the spectroradiometer.

3.2 *The influence of porosity*

The spectral transmissivity of all black nets is almost constant in the PAR range (fig. 5a) and it is strongly dependent on the porosity of the net (fig. 5b). Black net behaviour is "mechanical" because the net threads are completely opaque and the solar radiation passing through the net is not modified by the net.

High values of transmissivity, more than 70%, characterise nets with transparent threads. In the PAR range transparent nets do not cause an alteration of the spectrum of solar radiation and transmittance is almost constant with a slight growth in nets having a lower porosity (fig. 6a). The relation between the porosity and the average transmittance of the net in the PAR range can be described, with a good reliability, by the linear function:

$$\tau_{PAR}=0.39\Phi+0.62 \quad (1)$$

Consequently, the intersection of the line with the ordinate axe (φ=0) represents the transmissivity of a non permeable covering made of the net material having the same thickness of the net (fig. 6b).

The spectral transmissivity of green nets is strongly dependent on their tonality: dark green nets OMB50, OMB70 and OMB90 are characterised by an almost constant transmissivity in the PAR range (fig. 7a). On the contrary lighter green nets SH50 and HEX show a variation of the spectral distribution with a peak of the transmissivity in the 500-550 nm range that is more evident in the HEX net characterised by a Raschel fabric made of a very light green monowire. The correlation between the porosity and the average transmittance of the net in the PAR range can be described, with a good reliability, by the linear function:

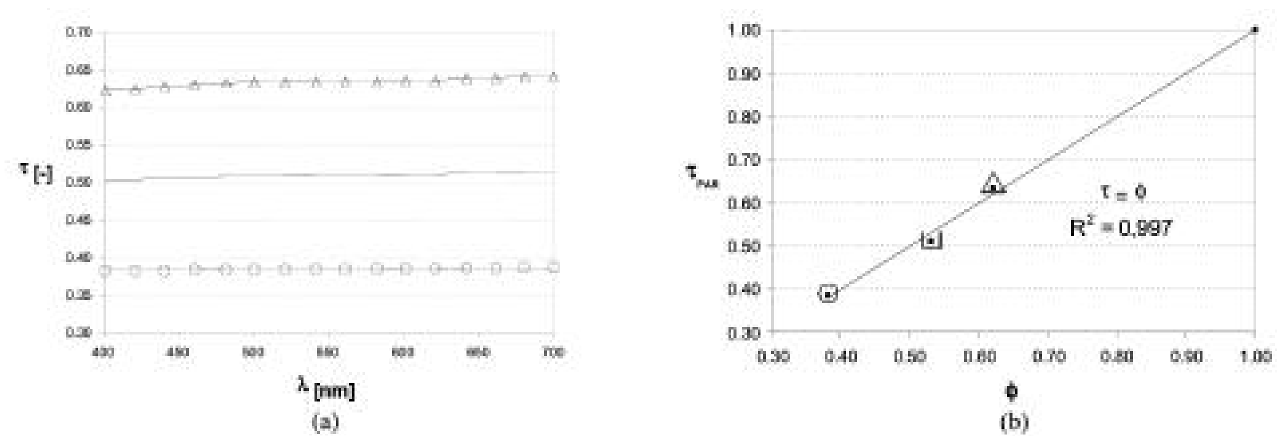

Fig. 5 - Black nets: transmissivity in the PAR (400-700 nm) range (a) and relation between the porosity (φ) and the medium value of transmissivity (τ_{PAR}) in the PAR range (b). SC75B ○, AGR50 □, SC50B Δ.

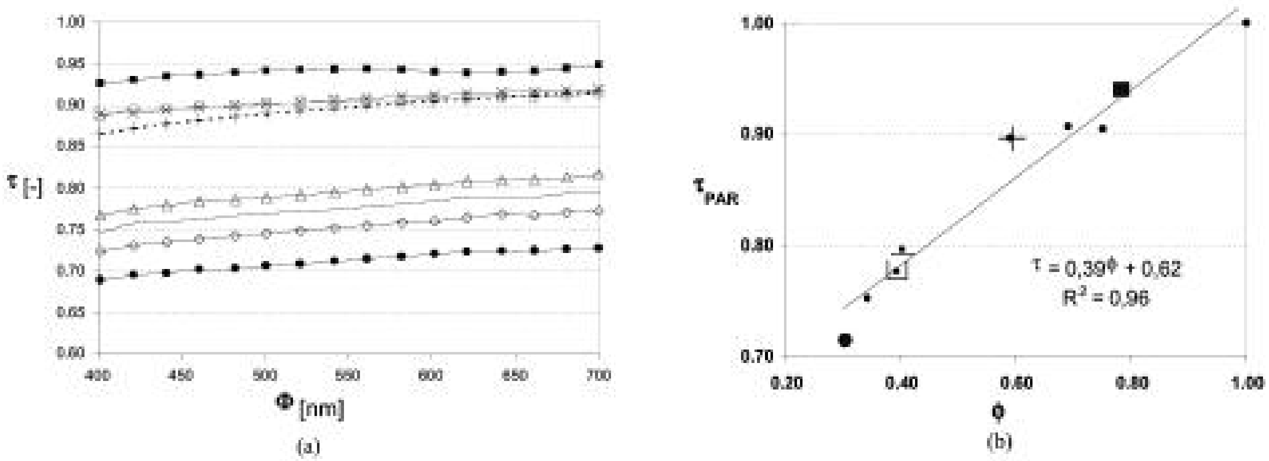

Fig. 6 - Transparent nets: transmissivity in the PAR (400-700nm) range (a) and relation between the porosity (φ) and the medium value of transmissivity (τ_{PAR}) in the PAR range (b). INST •, BIO50◇, ANTH□, BIO40 Δ, INSM +, INSK X, IMP ○, FR4.4 ■.

$$\tau_{PAR} = 0.96\Phi + 0.06 \qquad (2)$$

The intersection of the line with ordinate axe (φ=0) represents the transmissivity of a green non permeable covering made of the net material having the same thickness of the net (fig. 7b). Equation (2) shows a strong dependence of the transmissivity with the porosity depending on the relatively high porosity of the nets, on the dark tonality of the green and finally on the presence of tapes which, modifying their shape and superimposing to other tapes, provide to reduce the transmissivity of the whole net and indeed all the nets of the set are mainly employed as shading nets.

The peak of the spectral distribution transmissivity around 500-550 nm wavelength can be observed also in nets formed of black and green wires, because the shape of the curve is influenced by the green component of the net (fig. 8a). Figure 8b highlights also for this kind of net the linear dependence of the porosity with the transmissivity.

$$\tau_{PAR} = 0.88\Phi + 0.13 \qquad (3)$$

3.3 *The influence of colour*

The evaluation of the transmissivity values shows that the colour of a net influences the spectral distribution of the radiation passing through the net (fig. 9) absorbing their complementary colour. Figure 9 shows the transmissivity of shading nets in the range 300-800nm characterised by different colours of the threads and a porosity lower than 53%.

The transmissivity of black nets (fig. 5 and fig. 9) is almost constant in the visible range and the reduction of the incoming radiation is proportional to the solidity of the net. Concerning white nets (fig. 9) the transmissivity increases with the wavelength, the low values measured in the UV range are due to the presence of anti-UV additives. Blue nets (fig. 9) show peak values in transmissivity, τ=0.75, corresponding to λ=470 nm and minimum values, τ=0.32, in the range λ=600-760 nm corresponding to the red part of the spectrum. Green nets (fig. 7, fig. 8, fig. 9, fig. 10), depending on the hue of the colour (fig. 8 and fig. 10), highlight a wider interval, λ=450-570 nm, correspon-

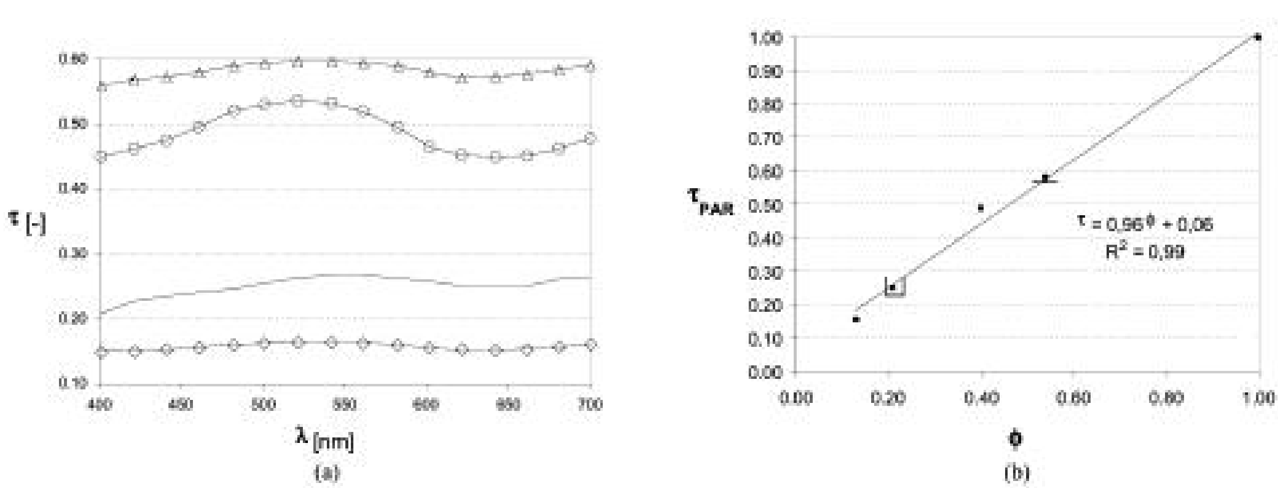

Fig. 7 - Green nets: transmissivity in the PAR (400-700nm) range (a) and relation between the porosity (φ) and the medium value of transmissivity (τ_{PAR}) in the PAR range (b). OMB90 ◇, OMB70 □, SH50 ○, OMB50 Δ.

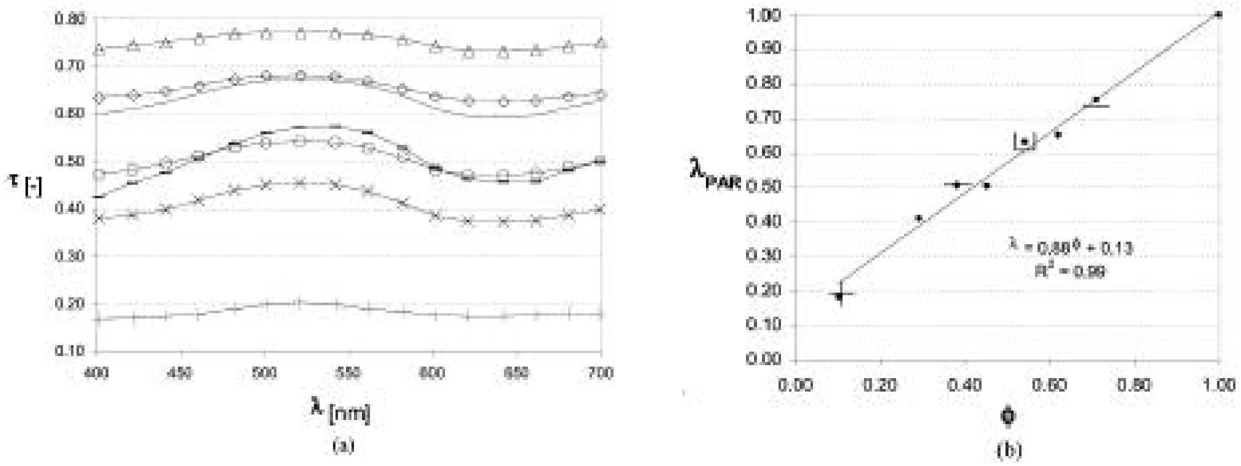

Fig. 8 - Nets with black and green threads: transmissivity in the PAR (400-700nm) range (a) and relation between the porosity (φ) and the average value of transmissivity (τ_{PAR}) in the PAR range (b). TS065 +, LIB70 X, BRWT -, LIB60 ○, LIB50 □, SCMD ◇, LIB30 Δ.

ding to maximum values of transmissivity whilst the minimum values of transmissivity are measured in the orange part of the spectrum, λ=630-670 nm. The same behaviour is highlighted for red nets, the curve of transmissivity quickly increases, passing from τ=0.37 to τ=0.68 in the range λ=580-620 nm, then continues to increase smoothly reaching the maximum value τ=0.78 at the upper bound of the visible range λ=760 nm (fig. 9). The minimum values of transmissivity are measured in the blue-green part of the visible range λ=460-580 nm.

The same behaviour of the curve of transmissivity is highlighted in nets with high porosity (φ=82%) and formed by transparent warps and wefts of different colours (fig. 10), the differences of peaks and lowest values (fig. 9 and fig. 10) depends on the amount of coloured threads with respect of the net surface. The total transmissivity of net TB (transparent and blue) shows a maximum corresponding to λ=460-470 nm then it decreases to its minimum value in λ=550-570 nm and continues almost constant to the end of the PAR range (fig. 10). Net TY (transparent and yellow) shows an increasing behaviour of the transmissivity

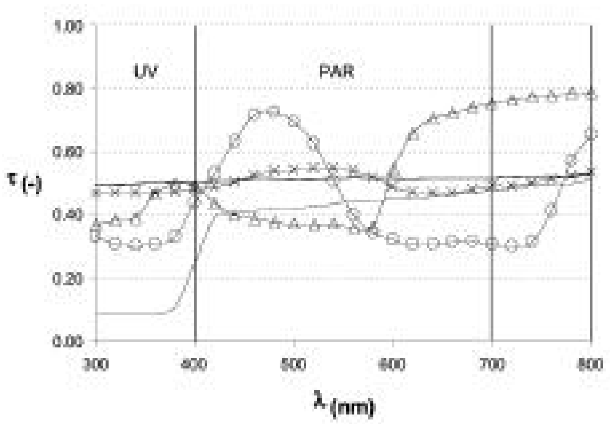

Fig. 9 - Transmissivity in the 300-800nm range measured for five nets characterised by different colours. AGR50 (Black) —, AGXW (White) □, SHB (Blue) ○, SHR (Red) Δ, SH50 (Green) X.

curve, the trend is linear with a flex almost in λ=510 nm (fig. 10).

Nets with a light green colour have an almost sinusoidal behaviour with a maximum in the range of 500-550 nm and a minimum corresponding almost to λ=600 nm. Nets with dark green threads show a smoother behaviour depending on the lower transmissivity of the dark green threads. It is interesting to notice that TDG shows higher average values of transmissivity in the PAR range than TLG, only locally at 500-550 nm the peak in the transmissivity curve of nets with light green threads is higher than the dark green one. The transmissivity of nets with red threads (TR) shows a minimum value in the range of 500-550 nm, then it increases almost asymptotically to its maximum value at 700 nm (fig. 10). The comparison of diagrams highlights that - even if TB and TR have an average transmissivity in PAR lower than TT - TR shows higher transmissivity values in the red part of the range whilst TB shows higher values in the blue part of the PAR range (tab. 6).

3.4 *The influence of the angle of incidence of the radiation source*

Except for its construction parameters, the radiometric performances of the nets in field condition are influenced by the position of the sun, azimuth and elevation, by the shape of the structure, and, only for knitted nets with tapes, by the orientation of weft and warp.

The influence of the position of the sun was investigated in the laboratory (fig. 11) on the same typologies of nets like those installed at the experimental screen house (fig. 5b) and compared with greenhouse glass. The transmissivity of the tested nets decreases with increasing elevation of the light source. It is possible to highlight a first part of the diagram, with an inclination from 0° to 45°, in which the transmissivity decreases very slowly and could be considered almost constant, and a second part, from 45° to 75°, in which

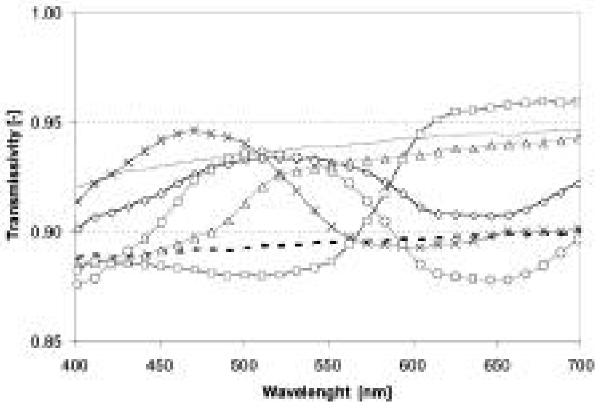

Fig. 10 - Field test transmissivity values in the PAR range for nets with transparent warps and transparent, TT —, blue, TB X, light green, TLG ○, dark green, TDG ◇, yellow, TY Δ, red TR □, and black wefts, TBL - - -.

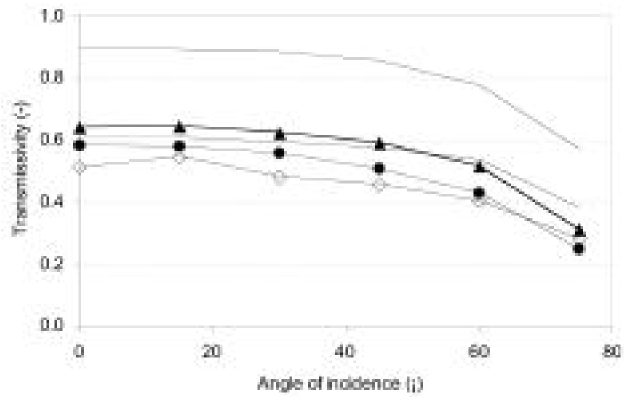

Fig. 11 - Transmissivity of four different nets depending on the angle of incidence of the radiation beam, 0° refers to the source perpendicular to the membrane.

the transmissivity decreases more quickly with a reduction of almost 40% (fig. 11). It is possible to notice that the diagram is less regular for nets than for glass, especially for AGR50 and OMB50 which were knitted net with tapes and mono-wires. In this case the position and the inclination of the tape with respect to the surface of the membrane influence locally the dimension of the empty part of the net of the holes and, consequently, the amount of radiation passing through the net.

In order to evaluate the influence of the warp or weft direction at the installation of knitted nets made by tapes with respect to the transmissivity of the net varying the angle of incidence of the radiation source, it was compared with the small integrating sphere, the transmissivity of three nets with the same construction typology but with different porosity at different angle of incidence position (fig. 12).

The position of the warp or of the weft with respect to the radiation source does not affect the transmissivity of the net, if the angle of incidence is lower than 40° (fig. 12). The different behaviour in warp and weft direction is affected by the porosity of the net (fig. 12) and it is empathised with an increasing porosity of the net.

With the increasing angle of incidence the transmissivity of the net is lower if the warp is perpendicular to the direction of the radiation source for OMB50. The test shows that for lower porosity the effect is the opposite even if the diagrams of transmissivity in the warp and weft direction are almost coincident.

4. Conclusions

Several nets with different texture, porosity, colours for various agricultural purposes were investigated concerning their radiometric properties. Nets are non-uniform materials, for this reason, radiometric properties should be studied on large enough samples to avoid any small-size effects. Measurements in the laboratory under defined conditions with an integrating sphere are suitable to characterise the net performance in the open field. Small differences, less than 5%, between laboratory and open field tests occur when measurements in the lab are carried out with a perpendicular artificial light source. Lab measurements should be carried out under different angles of incident as well to characterise the nets and to predict the agricultural performance. Results highlighted that the porosity and the mesh size combined with the colour and, secondarily, with the fabric and the kind of threads

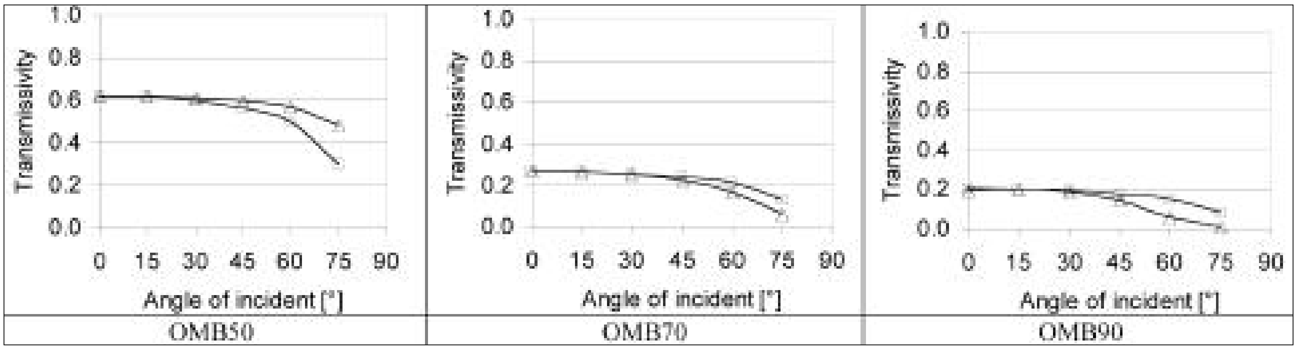

Fig. 12 - Transmissivity of three different nets depending on the sun's position, 0° refers to the source perpendicular to the membrane.

of the net influence the amount of radiation passing through the net and consequently the shading performance of the net. Moreover, the colour of a net influences the spectral distribution of the radiation passing through the net absorbing their complementary colours, confirming that the choice of the colour of the net combined with the radiation requirements of the plant could be strategic to optimize the crop production.

If the transmissivity could be considered one of the main parameters involved in the choice of agronomic requirements of the netting system, the reflectivity of the net is strictly involved in the aesthetic assessment of the net-house in the rural landscape. In this case nets with lower values of reflectivity should be chosen in order to reduce the visual impact of the building.

Nets should be chosen by growers carefully. Nets with an expected shading factor should have a high transmission for diffuse light. Insect nets and anti-hail nets should have light transmission as high as it is possible. Woven and English woven nets show a higher transmissivity than knitted nets. Since nets are three-dimensional structures the transmissivity of direct light under different angles of incident changes when installed in the warp or weft direction. Advanced light models are needed to estimate the total radiometric performance of net covered greenhouse structures.

Acknowledgements

This research has been funded by the European Commission sixth framework programme SME-2003-1-507865 "AGRONETS" (http://www.agronets.aua.gr/). The contribution to the programming and executing of this paper must be equally divided by the authors.

References

Antignus Y., Lapidot M., Hadar D., Messika Y., Cohen S. (1998). Ultra violet-absorbing screens serve as optical barriers to protect crops from virus and insect pests. Journal of Economic Entomology, 91(6), 1401-1405.

ASTM D1003-07 (2007). Standard Test Method for Haze and Luminous Transmittance of Transparent Plastics. ASTM (American Society for Testing and Materials) International.

Bailey B.J., Montero J.I., Parra J.P., Robertson A.P., Baeza E., Kamaruddin R. (2003). Airflow resistance of greenhouse ventilators with and without insect screens. Biosystems Engineering, 86(2), 217-229.

Castellano S., Hemming S., Russo G., (2008). The influence of colour on radiometric performances of agricultural nets. acta hort. (ISHS) 801: 227-236.

Castellano S., Scarascia Mugnozza G., Russo G., Briassoulis D., Mistriotis A., Hemming S., Waaijenberg D. (2008a). Plastic nets in agriculture: a general review of types and applications. applied engineering in agriculture. Applied Engineering in Agriculture. Vol. 24 (6); p. 799-808, ISSN: 0883-8542.

Castellano S., Scarascia Mugnozza G., Russo G., Briassoulis D., Mistriotis A., Hemming S., Waaijenberg D. Design and use criteria of netting systems for agricultural production in Italy. J. of Ag. Eng. - Riv. di Ing. Agr. (2008b), 3, 31-42.

Castellano S., Russo G., Scarascia Mugnozza G. (2006). The influence of construction parameters on radiometric performances of agricultural nets. Acta Horticulturae, 718, 718, 283-290.

Demrati H., Boulard T., Bekkaoui A., Bouirden L. (2001). Natural ventilation and microclimatic performance of a large-scale banana greenhouse. Journal of Agricultural Engineering Research, 80 (3), 261-271.

Elad Y., Messika Y., Brand M., David D.R., Sztejnberg A. (2007). Effect of colored shade nets on pepper powdery mildew (Leveillula taurica). Phytoparasitica, 35 (3): 285-299.

EN410 (1998). Glass in building. Determination of luminous and solar characteristics of glazing. ISBN 058030154 0.

Fatnassi H., Boulard T., Bouirden L. (2003). Simulation of climatic conditions in full-scale greenhouse fitted with insect-proof screens. Agricultural and Forest Meteorology, 118 (1-2), 97-111.

Fatnassi H., Boulard T., Demrati H., Bouirden L., Sappe G. (2002). Ventilation performance of a large Canarian-type greenhouse equipped with insect-proof nets. BIOSYSTEMS ENGINEERING, 82(1), 97-105.

Harmanto Tantau H.J., Salokhe V.M. (2005). Microclimate and air exchange rates in greenhouses covered with different nets in the humid tropics. Biosystems Engineering, 94(2), 239-253.

Hemming, S., Tom Dueck, Jan Janse, Filip van Noort (2007). The effect of diffuse light on crops. Paper and presentation during ISHS symposium Greensys 2007 – High Technology for Greenhouse System Management 4-6 October 2007 in Naples/Italy.

Hemming S., van Os E.A., Hemming J., Dieleman J.A. (2006). The Effect of New Developed Fluorescent Greenhouse Films on the Growth of Fragaria x ananassa 'Elsanta'. Europ.J.Hort.Sci., 71(4), 145-154.

Hemming S., van der Braak N., Dueck T., Elings A., Marissen N. (2005). Filtering natural light by the greenhouse covering – More production and better plant quality by diffuse light? – International Symposium on Artificial Lighting in Horticulture Lightsym2005 in Lillehammer, Norway, June 2005. Acta Horticulturae, 711, 105-110.

Hemming S., Waaijenberg D., Bot G.P.A., Dueck T., van Dijk C., Dieleman A., van Rijssel E., Houter B., Sonneveld P.J., de Zwart F., Marissen N. (2004). Optimaal gebruik van natuurlijk licht in de kastuinbouw. Wageningen UR report 100, ISBN 90-6757-767-0.

Impron I., Hemming S., Bot G.P.A. (2007). Effects of Cover Properties, Ventilation Rate and Crop Leaf Area on Tropical Greenhouse Climate. Biosystem engineering. Volume: 99, Issue: 4, April, 2008, pp. 553-564.

ISO 9050 (2003). Glass in building - Determination of light transmittance, solar direct transmittance, total solar energy transmittance, ultraviolet transmittance and related glazing factors. International Organization for Standardization.

Kittas C., Baille A. (1998). Determination of the Spectral Properties of Several Greenhouse Cover Materials and

Evaluation of Specific Parameters Related to Plant Response. Journal of Agricultural Engineering Research 71, 193-202.

Klose F., Tantau H.J. (2004). Test of insect screens - Measurement and evaluation of the air permeability and light transmission. European Journal of Horticultural Science, 69(6), 235-243.

Kumar P., Poehling H.M. (2006). UV-blocking plastic films and nets influence vectors and virus transmission on greenhouse tomatoes in the humid tropics. Environmental Entomology, 35(4), 1069-1082.

Miguel A.F., van de Braak N.J., Bot G.P.A. (1997). Analysis of the airflow characteristics of greenhouse screening materials. Journal of Agricultural Engineering Research, 67(2), 105-112.

Miguel A.A.F. (1998). Transport phenomena through porous screens and openings. PhD thesis University Wageningen, The Netherlands.

NEN 2675: 1990 nl (1990). Vlakglas - Tuinbouwglas - Bepaling van de lichtdoorlatendheid. Nederland nationale normalisatie-instituut.

Oren-Shamir M., Gussakovsky E.E., Shpiegel E., Nissim-Levi A., Ratner K., Ovadia R., Giller Y.E., Shahak Y. (2001). Coloured shade nets can improve the yield and quality of green decorative branches of Pittosporum variegatum. Journal of Horticultural Science & Biotechnology, 76 (3), 353-361.

Pearson S., Wheldon A.E., Hadley P. (1995). Radiation transmission and fluorescence of nine greenhouse cladding materials. Journal of Agricultural Engineering Research 62, 61-70.

Scarascia Mugnozza G., Russo G., Vox G. (1998). New calculation methodology of greenhouse covering materials transmittance. Proceedings of the 13th C.I.G.R. International Congress of Ag. Eng. - Rabat, Morocco, 2-6/2/1998, Vol. 2: 425-435.

Shahak Y., Gussakovsky E.E. (2004a). ColorNets: Crop Protection and Light-Quality Manipulation in One Technology. Acta Horticulturae 659, 143-151.

Shahak Y., Gussakovsky E.E., Cohen Y., Lurie S. (2004b). ColorNets: A New Approach for Light Manipulation in Fruit Trees. Acta Horticulturae, 636, 609-616.

Shahak Y., Yehezkel H., Matan E., Posalski I., Ratner K., Offir Y., Gal E., Ben-Yakir D. (2007). Photoselective netting improves productivity of bell peppers. Hortscience, 42(4), 851-851.

Soni P., Salokhe V.M., Tantau H.J. (2005). Effect of screen mesh size on vertical temperature distribution in naturally ventilated tropical greenhouses. Biosystems Engineering, 92(4), 469-482.

Teitel M. (2007). The effect of screened openings on greenhouse microclimate. Agricultural and Forest Meteorology, 143(3-4), 159-175.

Teitel M., Peiper U.M., Zvieli Y. (1996). Shading screens for frost protection. Agricultural and Forest Meteorology, 81(3-4), 273-286.

UNI, (1994). Italian National Standard 10335, Nets for agricultural applications- determination of the shading power of nets of polyethylene fibre. Ente Nazionale Italiano di Unificazione, Italy.

Valera D.L. (2005). Contribution to characterization of insect-proof screens: experimental measurements in wind tunnel and CFD simulation. Acta Horticulturae, 691 441-448.

Varlet-Grancher C., Gautier H. (1995). Plant morphogenetic responses to light quality and consequences for intercropping. In: Sinoquet H., Cruz P. eds. Ecophysiology of tropical intercropping. INRA editions, Versailles, 231-256.

Summary

Nets are commonly used for agricultural applications. However, only little is known about the radiometric properties of net types and how to influence them. In order to investigate the influence of net construction parameters on their radiometric properties, a set of radiometric tests were performed on 45 types of agricultural nets. Laboratory tests on large size net samples was performed using a large and a small integrating sphere. Open field radiometric test were carried out by means of an experimental set up (120x120x50 cm) and a full scale shade house. Small differences (less than 5%) occurred between laboratory and open field tests. Results highlighted that the porosity and the mesh size, combined with the colour and secondarily, with the fabric and the kind of threads of the net influenced the shading performance of the net. The colour influenced the spectral distribution of the radiation passing through the net absorbing its complementary colours. Since nets are three-dimensional structures the transmissivity of direct light under different angles of incident of solar radiation changes when installed in the warp or weft direction. Transmissivity could be considered one of the main parameters involved in the agronomic performances of the netting system.

Keywords: agricultural nets, permeable coverings, radiometric properties, open field test.

List of symbols

$BaSO_4$	Barium Sulphate
HDPE	High Density Poly-Ethylene
PAR	Photosynthetic Active Radiation range 400-700 nm
MAR	Morphogenetic Active Radiation range 780-2500 nm
NIR	Near Infrared Radiation range 780-2500 nm
φ	Porosity of the net
ρ_{PAR}	Reflectivity in the PAR range
σ_{PAR}	Haze (percentage of the transmitted radiation scattered by a material) in the PAR range
τ_{PAR}	Total (direct + diffuse) transmissivity in the PAR range
τ_{NIR}	Total (direct + diffuse) transmissivity in the NIR range
τ_{SOL}	Total (direct + diffuse) transmissivity in the solar range (300-2500 nm)
$\tau_{PAR\ dir}$	PAR transmissivity for direct light
$\tau_{PAR\ diff}$	PAR transmissivity for diffuse light