Thermal Evaluation of a Greenhouse in a Remote High Altitude Area of Nepal

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Abstract – *Remote communities in the high altitude areas of Nepal suffer both chronic and acute malnutrition. This is due to a shortage of arable land and a harsh climate. For seven months of the year, the harvesting of fresh vegetables is almost impossible. Greenhouse technology, if appropriate for the location and its community, can extend the growing season considerably. Experience in the Ladakh region of India indicates that year-round cropping is possible in greenhouses in cold mountainous areas. A simple 50-m^2 greenhouse has been constructed in Simikot, the main town of Humla, northwest Nepal. This paper describes the evaluation of the thermal performance of that greenhouse. Both measurement and simulation were used in the evaluation. Measurements during the winter of 2006-7 indicate that the existing design is capable of producing adequate growing conditions for some vegetable crops, but that improvements are required if crops like tomatoes are to be grown successfully. Options to improve the thermal performance of the greenhouse have been investigated by simulation. Improvements to the building envelope such as wall insulation, double-glazing and using a thermal screen were simulated with a validated TRNSYS model. The impact of the addition of nighttime heat from internal passive solar water collectors was also predicted. The simulations indicate that the passive solar water collectors would raise the average greenhouse air temperature by 2.5°C and the overnight air temperature would increase by 4.0°C. When used in combination, overnight temperatures are predicted to by almost 7°C higher.*

Keywords – Energy conservation, greenhouse, Nepal, simulation, thermal performance.

1. INTRODUCTION

Nepal is a developing country and is ranked 142nd out of 177 countries in terms of Human Development Index [1]. In terms of income, Nepal is ranked 68th out of 102 developing countries with an annual GDP per capita of US$ 252 [2]. In 2007, the country had an estimated population of 28.9 million, of which 38% were aged 14 or less and approximately 80% of whom lived in rural areas [3]. In energy terms, traditional fuel consumption represents 93% of total usage and the average electricity consumption is only 91 kWh [2], although this is accessible to only approximately 25% of the population. Infant mortality, compared to developed nations, is high ranging from 86 to 53 per 1000 live births for the poorest and richest 20% respectively. The UNDP [2] estimates that in 2001-3, 17% of the population was estimated to be malnourished. In children under five years old, this was reflected in 48% and 51% being under weight and under height for age respectively. Over one fifth of babies were born underweight. These average statistics, alarming as they are, mask a more serious situation for rural and remote people in Nepal, where malnutrition and its effects are much worse.

Food security is defined as “a situation that exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life” [4]. As part of an aim to improve general food security, a small number of simple greenhouses have been built by a local NGO - Rural Integrated Development Services - Nepal (RIDS-Nepal) in a high altitude area of Nepal. This paper describes the evaluation of the first of these greenhouses in Simikot (latitude: 29.967; longitude: 81.833; altitude: 3000 m), the main town of the province of Humla in the northwest of the country. The purpose of the evaluation was to determine the effectiveness of the current design and to determine possible design improvements. The paper first presents an overview of the location of the greenhouse, including climatic conditions. The greenhouse is then described, followed by an outline of the methodologies used to evaluate the thermal performance of the greenhouse. The results of the evaluation are then presented and discussed, followed by some possible design improvements and the impact that these may have.

2. THE HUMLA VALLEY

According to [5], Nepal can be divided into seven natural topographical “units”, which can be clearly distinguished from each other. One of these regions is known as the Inner Himalayas. It is the name given to the valleys, which lie to the north of Nepal’s principal and well-known chain of mountains, the Himalayas. Hagen [5] describes these inner valleys as “the real high mountain valleys of Nepal, surrounded on all sides as they are by ice clad giants”. One of these valleys, located on the western end of the country, is the Humla valley, which is over 400 km northwest of Kathmandu (Figure 1). Of the 75 provinces in Nepal, Humla has been judged to be one of the poorest. Using a ranking of 1 (best) to 75 (worst), Humla was ranked in the overall index at 74th position in terms of

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poverty, deprivation, socioeconomic and infrastructural development, and women empowerment [6]. In reality, this means, for example, that there is no road infrastructure in the district, and people and goods are transported on foot or by animal along mountain tracks. The airstrip at Simikot, which provides the main link to the outside world, is unmade and there are no regular scheduled flights.

According to [7], "in this food deficient area, a subsistence economy runs on inter-village trade, livestock and the cultivation of food-grains ". Only two percent of the land is arable due to steep slopes, rocks and forest cover. In addition, snow cover for five months of the year further reduces the opportunity for year-round fresh food production As a result, and unsurprisingly, there is chronic malnutrition among the local population. In a study of children in the districts of Humla and Mugu, it was found that global acute and chronic malnutrition rates were 12.3% and 63.9% respectively [8]. As the Nepal Trust [7] succinctly states “survival is a serious business for the people of the Hidden Himalayas”.

Low average daily ambient temperatures (Table 1), accompanied by even lower average overnight minimum temperatures and snow, means that little can be grown outside between November and March in the Humla Valley. Planting outside begins in early April but little fresh produce is harvested until the end of May resulting in almost seven months of a fresh food deficit, particularly vegetables. Despite the low monthly winter temperatures, the solar radiation levels over the winter months (Table 1) suggest that an appropriate greenhouse technology could be used to increase food production. Greenhouses built in other high altitude areas have demonstrated that growing seasons can be greatly extended, even achieving year-round production in some cases

Fig. 1. Map of Nepal highlighting Simikot – location of greenhouse.

Table 1. Climatic summary of data collected at Simikot between May 2004 and March 2007.

Month	Average Monthly Horizontal Solar Radiation (MJ/m^2/d)	Average Monthly Ambient Temperature (°C)	Average Monthly Maximum Ambient Temperature (°C)	Average Monthly Minimum Ambient Temperature (°C)
January (82)	12.6	6.6	13.2	-1.4
February (55)	14.0	6.6	14.5	1.2
March (79)	17.4	8.1	15.4	2.5
April (44)	20.1	11.5	17.8	6.0
May (93)	19.0	14.5	20.0	9.4
June (90)	17.2	17.1	22.6	12.3
July (93)	14.9	17.9	22.5	14.9
August (77)	14.7	17.2	22.2	14.0
September (57)	17.7	16.8	22.6	12.4
October (39)	16.7	12.4	19.5	6.4
November (42)	14.2	8.5	17.4	1.1
December (93)	12.1	7.4	16.0	1.1

Note: (Figures in brackets indicates number of days of complete data)

3. HIGH ALTITUDE GREENHOUSE

While protected horticulture is increasingly practiced in many developing countries, the particular characteristics of Nepal pose special problems. The country is the poorest in South Asia and its mountainous terrain has severely impeded infrastructure development. In Humla, as noted earlier, there are no vehicles or electricity and only a limited number of commercial enterprises. Thus solutions which might have been used elsewhere are often simply not feasible. Some success with high altitude greenhouses for vegetable production in the Ladakh region of India has been reported [9]. The walls of these 50 m^2 solar greenhouses were constructed from sun-dried bricks, insulated with straw and UV-stabilised polyethylene was used as the glazing. More than 100 greenhouses were built within three years from 1998. It is estimated that it is possible to earn US$ 50 per month for about two hours work inside a greenhouse each day.

Experience with greenhouses at high altitudes in Nepal for food is more limited, although the idea of protected cropping is not unknown. Many small low polyethylene-covered structures can be seen around Simikot, for example (Figure 2). Introduced in 2004 by a Nepali NGO (Appropriate Technology Asia), these structures are used only for frost protection and propagation. To the authors' knowledge, there are few, if any, genuine greenhouses designed for year-round intensive food production in the area. One of these is in the town of Simikot and is the focus of this evaluation.

Fig. 2. Example of simple polyethylene growing structures around Simikot.

Fig. 3. External view of the HARS greenhouse at Simikot.

Fig. 4. Internal view of HARS greenhouse at Simikot.

4. THE HARS GREENHOUSE

As part of their food security and nutrition programme, RIDS-Nepal constructed a small greenhouse at their High Altitude Research Station (HARS) at Simikot in September/October 2004 (Figure 3). The HARS greenhouse design is simple and is built largely from locally available materials. The overall inside dimensions of the greenhouse are 10 m by 5 m. The south-facing roof is inclined at 15 degrees. This slope was dictated by site considerations and is far from ideal in terms of snow shedding or maximising penetration of winter solar radiation. There was also some shading at times of the year due to an adjacent building. The low profile of the building was also not ideal ergonomically**,** but the impact is minimized by short working periods. The walls are made of stone and mud, and the roofing frame is constructed from 75 mm by 50 mm timber. These are supported internally by vertical posts located in the ground. The glazing material is UV-stabilised polyethylene imported from India. Until late December 2006, a single glazing layer was used. Subsequently, a second layer of polyethylene was installed. The crop, which to date has largely been leaf vegetables such as spinach, is grown directly in the ground (Figure 4).

The local HARS staff uses the HARS greenhouse to grow their out-of-season vegetables. The thermal performance of the greenhouse, however, has not been evaluated, and therefore possible improvements have not been identified. Eight other similar greenhouses have already been installed in various villages in the upper Humla Valley in response to villagers' requests. It is important that the best design, consistent with local needs and infrastructure, is promoted. The thermal performance of the HARS greenhouse has therefore been evaluated using a combination of direct measurement and simulation.

5. MEASUREMENT

Various thermal performance data was collected from the greenhouse in the winter months November 2006 – March 2007. Total solar radiation on the horizontal plane outside the greenhouse was measured using an unshielded photoelectric pyranometer (Pacific Systems Pty. Ltd., SolData SPC80 SN 243, spectral range 300-2800 nm). Ambient temperature and relative humidity were also measured by a weather station (Spectrum Technologies, Inc., WatchDog Model ET900), which is part of the long-term data collection system at the HARS. The weather station is located adjacent to the greenhouse. Battery-powered data loggers (Onset Corp., Hobo H8 and U12-006 Series and TMC-HD temperature sensors) were used to measure internal greenhouse air and humidity at four locations within the greenhouse. Soil temperatures at 200, 600 and 2000 mm depth and just below the surface inside and outside the greenhouse were also measured with this type of sensor. These devices were cross-calibrated against each other at the start of the experiments. A hand-held hot wire anemometer (TSI Inc., VelociCalc Model No 8350-1) was used to measure air movement at various points in the greenhouse.

The data collected over the winter months of 2006-7 has been analysed to reveal key greenhouse performance data. Figure 5 illustrates the typical daily behaviour of the greenhouse in terms of temperature and relative humidity in mid-January 2007. The outside ambient overnight minimum temperature of -5.8°C occurs at approximately 6.30 am. On average, between midnight and sunrise, the greenhouse air temperature is approximately 7.5°C above the outside ambient temperature. Sunrise occurs at approximately 7 am and the outside ambient and greenhouse air temperatures start to rise soon afterwards. During the daytime the average greenhouse air temperature is approximately 12°C above the outside air temperature, with a peak of nearly 26°C at approximately 1 pm. The average greenhouse relative humidity is nearly 60%, approximately 20 percentage points above the ambient level. Horizontal solar radiation on the day is 13.8 MJ m^{-2}.

Figure 6 illustrates the typical daily behaviour of the soil inside and outside the greenhouse in terms of temperature in mid-January 2007. The temperature just below the surface of the soil inside the greenhouse follows approximately the same pattern as that outside the greenhouse but with a reduced swing and higher peak. During the nighttime, the sub-surface soil in the greenhouse is approximately 7-9 °C warmer than the outside sub-surface soil. At 200 mm, the temperature of the soil in the greenhouse does not fall below nine degrees centigrade. At 600 and 2000 mm depths, the soil temperature in the greenhouse is relatively constant at 10.3°C and 11.3°C respectively.

Figures 5 and 6 indicate that, while not ideal, growing conditions in the existing greenhouse are certainly suitable for some vegetable crops such as spinach, carrots and beans. Improvements in the thermal performance of the greenhouse such as increasing the overnight minimum air and soil temperatures will be beneficial to crop growth and productivity. The options for performance improvement can be best identified by simulation.

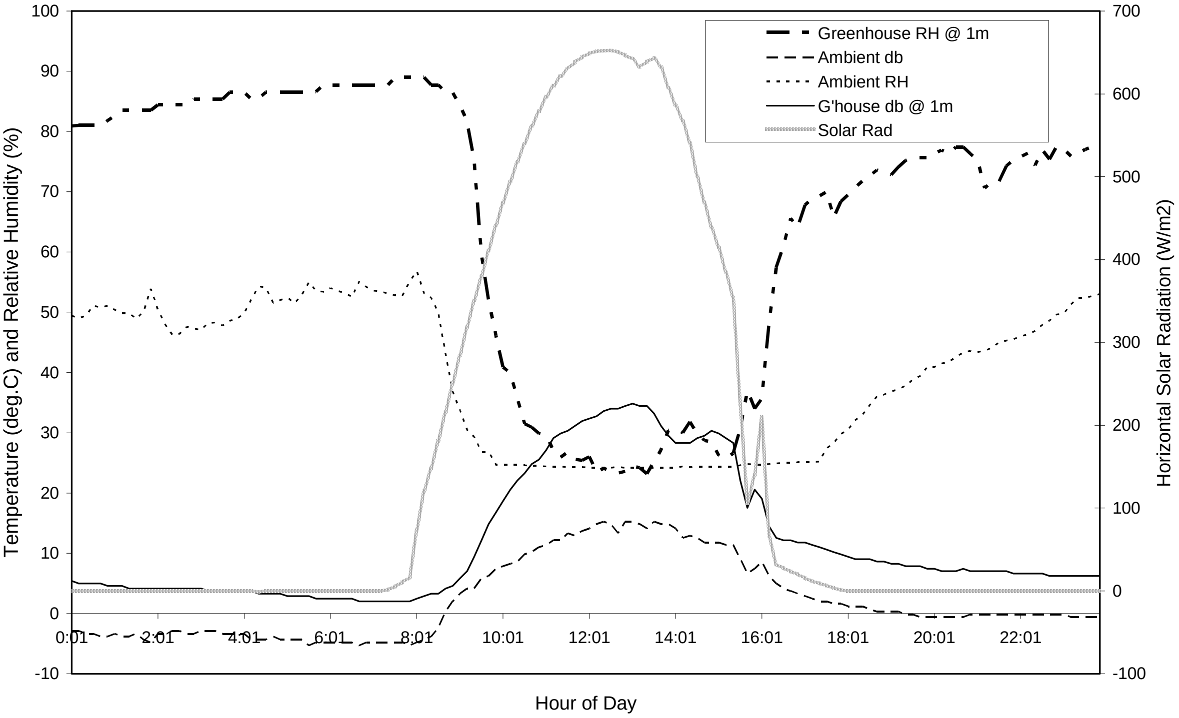

Fig. 5. Typical daily greenhouse air and relative humidity levels in mid-January.

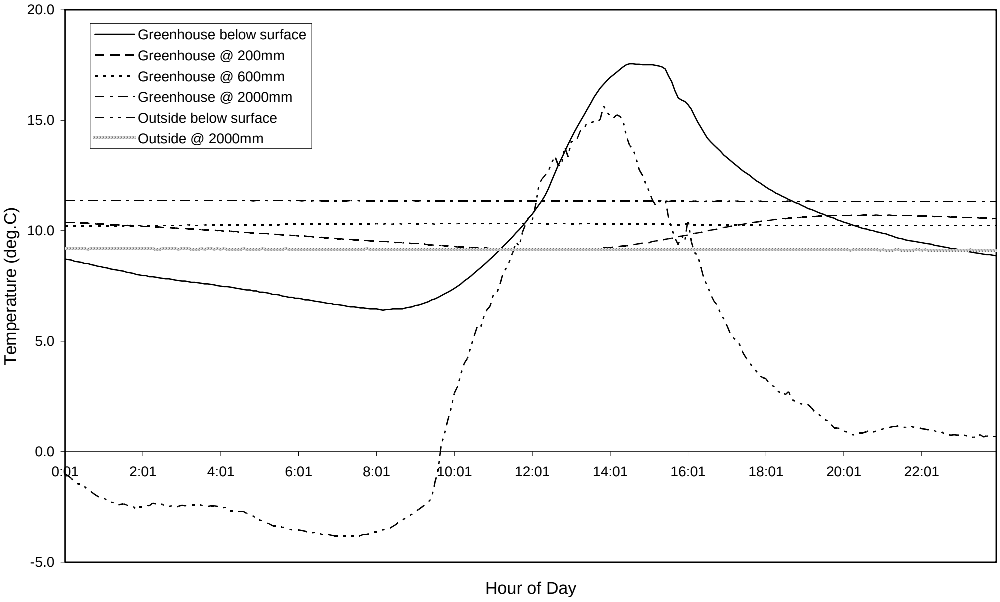

Fig. 6. Typical daily greenhouse and outside soil temperatures in mid-January.

6. SIMULATION MODEL

Numerous dynamic thermal models have been developed to investigate the thermal performance of greenhouses e.g. [10]. Most of these are relevant to the advanced type of protected horticulture practiced in industrialised countries. These models have been developed for structures where the glazed to opaque surface ratio is very high. In addition, cropping levels and therefore latent loads are also high. Thermal mass levels (apart from the floor) are very low. In these respects, the HARS greenhouse differs substantially from the modern horticultural greenhouse. The roof and less than half of the side-walls are the only glazed surfaces, and even here the ratio of structural members to glazing is high because the use of locally available materials and constructional skills has been maximized. All four walls are made of local stone, which provide substantial amounts of thermal capacitance. With respect to these two factors, the structure has more similarities to traditional building rather than a greenhouse. Cropping levels at this stage in the development of this technology in Nepal are also low compared to a modern greenhouse practice. For the above reasons, a more traditional building model has been used to investigate the greenhouse thermally rather than a specialist greenhouse model. The standard building sub-routine within TRNSYS (Type 56) has therefore been used. This model allows the user to define a building of any size or shape. User-supplied parameters define material properties and dimensions. Schedules can be used to determine inputs at specified time. A radiation processor within TRNYS uses horizontal radiation data to calculate hourly values of solar radiation on all of the building's surfaces.

6.1 Model Description

The Type 56 sub-routine requires various fixed parameters to be supplied and assumptions to be made by the user. Table 2 indicates the material properties used.

Several assumptions have been made and included in the model. An infiltration rate of 1.0 volume air change per hour is reasonable for a polyethylene-covered greenhouse. Until April 2007, there were no vents installed. The doors are small and often in winter these are not opened. Although a ground reflectance value of 0.7 is normally used when the ground is covered by snow, a value of 0.2 was used in these simulations because in mid-November this had not yet occurred. The north wall of the greenhouse is almost entirely buried by soil. Both this wall and the earth floor are assumed bounded by a thermal layer at a constant temperature of 12°C. This temperature was determined from soil temperature measurements made in November. Sky temperature was assumed to be constant throughout the simulations and set at ambient air temperature less 12°C. Although lower levels will occur when there are clear night skies, no cloud cover observations were available and an average value was therefore assumed. TRNSYS window library does not contain data for polyethylene and so a single layer of glass was assumed. While the solar and thermal properties of thin film polyethylene and glass are different, several factors reduced the impact of these differences. The polyethylene used was canvas-grade and therefore significantly thicker than the normal 150 micron horticultural grade, there was some dirt and moisture on both sides of the glazing reducing transmittance in all wavelengths and finally an opaque canvas was pulled over the glazing at night.

Table 2. Material properties used in TRNSYS simulations.

Material	Density, (kg m^{-3})	Conductivity, (W m^{-1}K^{-1})	Specific Heat Capacity, (kJ kg^{-1} °C^{-1})	Reference
Granite	2640	3.0	0.82	[11]
Earth	1200	0.37	0.88	[12] and [13]
Timber	700	1.4	2.60	[11]

6.2 Model Validation

The TRNSYS model of the HARS greenhouse was validated using one week of data collected in November 2006. A climatic data file of hourly values of global horizontal solar radiation, and ambient dry bulb temperature and relative humidity was constructed from the weather station data. Hourly predictions of greenhouse air temperature, relative humidity and soil surface temperature from the model were made and compared against actual measurements made at the same period (Figures 7, 8 and 9). Predicted air temperatures follow the same diurnal pattern as the average of the measured values, with the predicted rates of rise and fall in temperature following actual measurements well (Figure 7). Although the model tends to under-predict the daily maximum, the prediction of daily minimum temperatures shows better agreement. The under-prediction may be due to the higher solar transmittance of polyethylene film compared to glass.

The model has calculated the temperature of the soil at its surface. Since actual measurement of this temperature is not available, the prediction has been compared with the temperature of the soil 5 mm below the surface (Figure 8). Some difference between the prediction and the measurement is therefore understandable. The surface responds instantaneously to thermal inputs, whereas there is some delay, shown by the offset, in the response of sub-surface layers. Figure 6 also illustrates this behaviour in both outside and inside greenhouse soil temperatures.

Type 56 is a TRNSYS sub-routine designed to simulate the performance of buildings. Although the HARS greenhouse has many similarities with a conventional building, it also contains plants and soil, which add moisture to the surrounding air. Initial simulations did not include any humidity gain and the poor agreement between predictions of relative humidity against the measured value at one metre is evident in Figure 9. Unfortunately there are no records of water use in November. However, in the first three months of 2007, daily water use varied from 11-24 litres per day. Photographic records also indicate only a relatively low cover of young spinach plants in November 2006. Assuming that only five litres of water was used a day and that evaporation occurred evenly each day, the model was programmed to assume an hourly addition of 0.23 kg of moisture. Figure 9 shows that this assumption produced a good representation of reality, as the predictions of greenhouse relative humidity rise and fall in line with measurements.

7. PERFORMANCE IMPROVEMENTS

The measured and predicted results over a one-week period in November were considered to be accurate enough to have confidence in the use of the model for long term predictions. The validated model was therefore used to investigate various strategies to improve the performance of the HARS greenhouse. These include the use of a thermal screen, wall insulation and 'solar sleeves'. The following sections describe how these strategies were simulated and their impact.

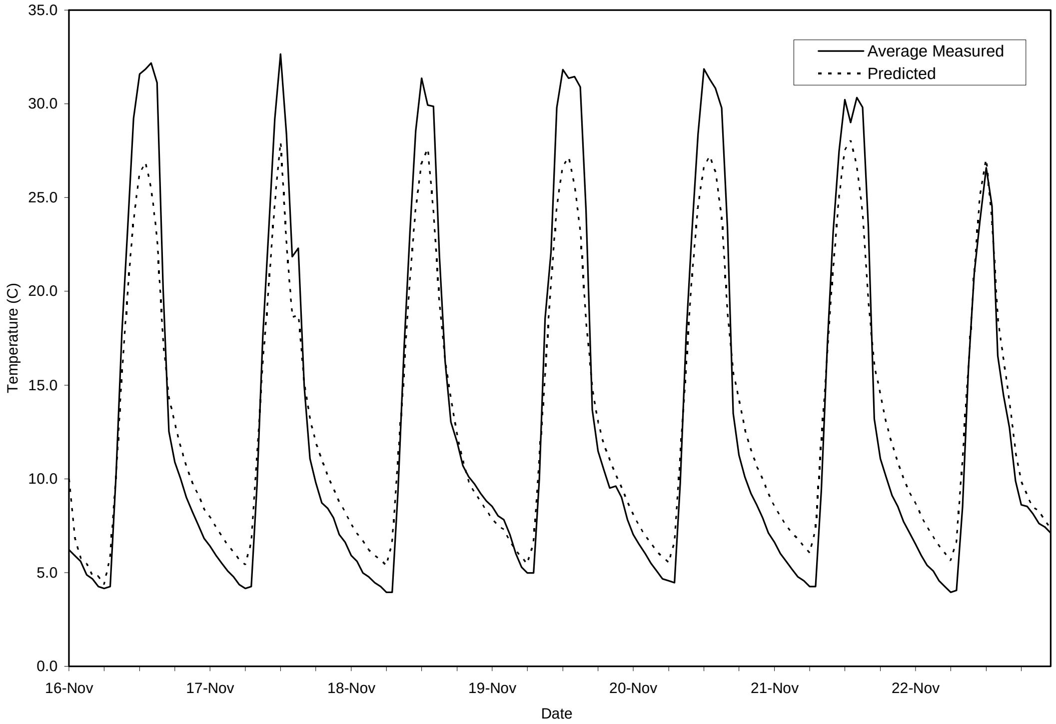

Fig. 7. Comparison of measured and predicted greenhouse air temperatures.

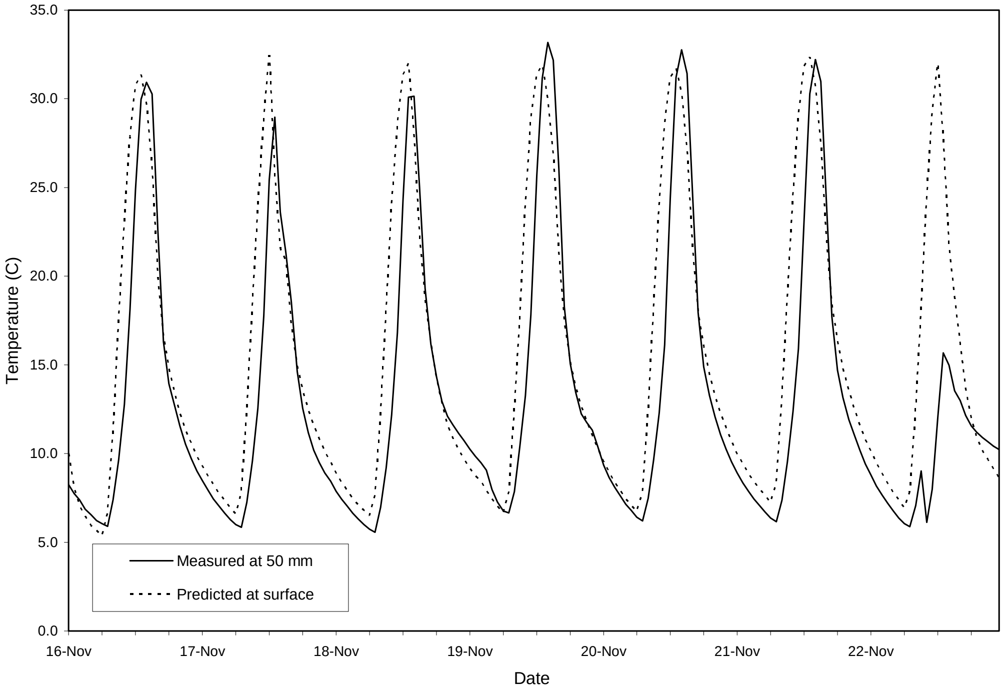

Fig. 8. Comparison of measured and predicted greenhouse soil temperatures.

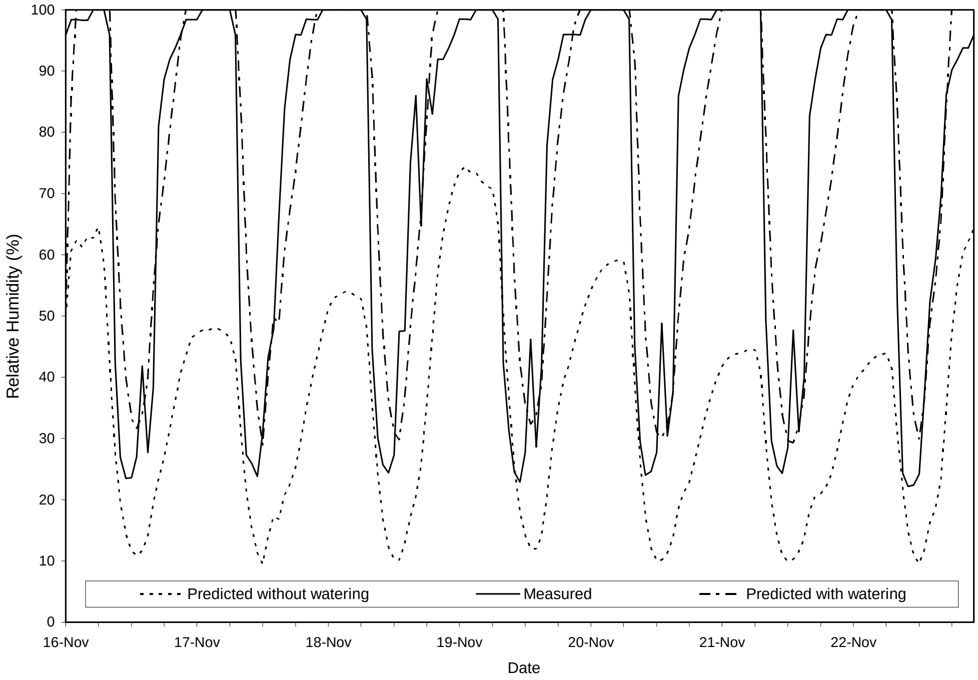

Fig. 9. Comparison of measured and predicted greenhouse relative humidity - with and without watering.

7.1 Thermal Screen

Thermal screens or night blankets made from multi-layers of advanced synthetic materials have been used in greenhouses in industrialised countries for approximately 30 years. Simpler versions of night blankets are in use in developing countries. Screens made of various materials are drawn across the crop at night and reduce nighttime heat losses from the greenhouse glazing caused by convection and radiation. A screen also reduces the volume of air in the greenhouse at night and this subsequently reduces heating requirements. Depending on the quality and complexity of the screen, fuel savings of up to 60% have been reported when screened and non-screened greenhouses have been compared.

It was not possible to simulate directly the addition of insulating layer within the greenhouse because any layer must be withdrawn during the day because the Wall Layer defined in the Type 56 subroutine are fixed throughout the simulation. An alternative approach was therefore used to simulate the effect of a thermal screen. The energy 'saved' by the change in the overall heat loss of the greenhouse was calculated at each time step. The energy saving is a function of the reduction in the overall heat loss for the greenhouse due to the thermal screen, the glazing area and the temperature difference between the greenhouse and outside air. This amount of energy was then introduced into the greenhouse as an energy 'gain' during the hours of thermal screen use. A reduction in overall heat loss of 1.8 Wm^2 $°C^{-1}$ was considered a realistic saving for the simple sort of thermal screen envisaged for the HARS greenhouse [14].

7.2 Wall Insulation

The present walls of the HARS greenhouse are 450-mm thick and made of granite. Some mud is used as mortar. Granite has a higher conductivity than concrete and is a poor insulator. An alternative construction technique could be envisaged in which a layer of insulating material is placed between two 200 mm thick walls. The most available insulating material in Humla is dried pine needles, which are already used as insulation in the roofs of the traditional dwellings in the area. Values of thermal conductivity (0.09 Wm^{-2} $°C^{-1}$), specific heat (0.28 $kJkg^{-1}$ $°C^{-1}$) and density (0.27 kgm^{-3}) for thatch, taken from [13], were used in the simulations in lieu of more precise data.

7.3 Solar Sleeves

Passive solar water heaters or ‘solar sleeves’ have reportedly been used successfully by researchers and growers in at least nine countries in southern Europe [15]. Water-filled transparent polyethylene film sleeves (320 mm diameter) are placed on strips of black plastic on top of 50 mm of insulation material between the crop rows (Figure 10). The ends of the sleeves are tied to stakes driven into the soil at the ends of each tube. During the day, solar radiation passes through the transparent sleeves, is absorbed by the black plastic sheet. The heat generated is transferred to the water in the sleeves. At night, the heat in the water is transferred to the greenhouse air by convection and to the adjacent plants by radiation. As the plants grow, they increasingly shade the sleeves and reduce their effectiveness. Their main benefit is therefore in establishing and promoting early growth. The system is both simple and inexpensive and therefore is potentially feasible for use in the Humla greenhouses.

A four-day experiment to determine the effectiveness of solar sleeves was conducted in April 2007 in the HARS greenhouse. Figure 11 shows the temperature rise and fall in the water contained in a 200 mm diameter tube, placed on flat black plastic polyethylene socks filled with dry pine needles. On the basis of these experiments, it was calculated that on average 94.0 MJ could be captured in the greenhouse during the day and released overnight, assuming that there are seven 5.0-metre tubes on the greenhouse floor, each containing 1120 litres of water. To determine the potential impact of the solar sleeves on greenhouse thermal performance, this amount of energy was released over a 12-hour period at night in the TRNSYS model.

Fig. 10. Solar sleeves inserted between crop rows.

7.4 Impact of Strategies

Since the HARS greenhouse is unheated, the impact of the strategies described above was determined by their predicted effect on nighttime air temperatures, rather than energy consumption. Table 3 shows their individual and combined impact during the same week used earlier to validate the model.

Almost all of the strategies impact positively on the indicators chosen. The one exception is that the use of 50 mm of pine needles in a cavity wall does not raise the absolute minimum overnight temperature experienced in the period. However, this strategy does raise the average greenhouse air temperature between 6 pm and 6 am. The advantage of this strategy is that no new materials or technologies are required, and no additional user action is needed. This strategy cannot be applied to the current greenhouse, but could be considered for future greenhouses. The thermal screen increases both the average and overnight minimum temperatures. It also has the potential to provide shade in summer. The disadvantages of a thermal screen in this environment are that the material must be imported and the user must operate the screen daily to achieve its benefits.

The most effective single strategy appears to be the solar sleeves, which raise the absolute minimum by 2.3°C and the average overnight temperature by 4.2°C. While they are the most effective in thermal terms, they do have some practical disadvantages. The sleeves reduce the productive growing area and make access in the greenhouse more difficult. In combination, the strategies are obviously superior to any single strategy. Overnight temperatures were predicted to be higher by over 7.3°C, and minimum experienced during the week was 7.1°C, compared to 4.4°C in the current design. The average air temperature in the greenhouse rose by 4.8°C compared to the current design.

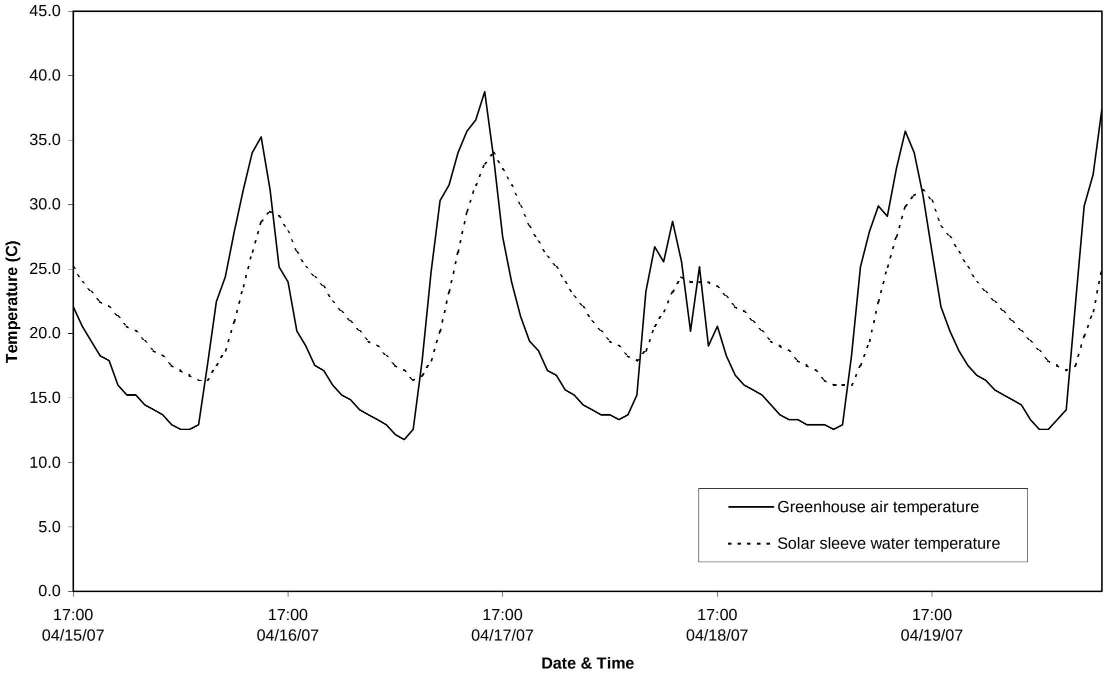

Fig. 11. Diurnal temperature of water in clear plastic tube in the HARS greenhouse.

Table 3. Predicted impact of individual and combined strategies on various greenhouse air temperatures.

Strategy	Average greenhouse air temperature during week (°C)	Average greenhouse air temperature between 6pm and 6am (°C)	Minimum overnight greenhouse air temperature during week (°C)
None	13.1	8.2	4.4
Thermal Screen	13.8	9.3	5.1
Wall Insulation	13.7	8.8	4.4
Solar Sleeves	15.7	12.4	6.7
Combined	17.9	15.5	7.1

8. CONCLUSION

The Humla valley is a remote and mountainous part of NW Nepal. The area suffers from permanent food deficit because of the harsh terrain and climate. For the five winter months of the year, it is impossible to grow fresh vegetables outside. Protected horticulture i.e. greenhouses are seen as a technology to improve and extend the fresh food supply. A simple greenhouse, constructed from local materials, has been operating at a research station in Simikot, the main town of the Humla District since October 2004. However, no systematic evaluation of the greenhouse and its thermal performance has been undertaken. The thermal performance of the design needs to be understood so that changes, if required, can be made and so the best and most appropriate technology is offered to potential users.

The greenhouse has therefore been evaluated through measurement and simulation. Measurements indicated that the conditions within the greenhouse are suitable for some vegetables but need to be improved if a wider variety and greater output is required. In order to evaluate possible design or other improvements, a simulation model using TRNSYS Type 56 was developed and validated against measurements. The predictions of the model were compared with greenhouse air and soil temperatures, and relative humidity measurements collected between November 16th and 22nd 2006. The model was considered to be sufficiently accurate to allow various energy saving and collection strategies to be evaluated. These were the provision of wall insulation, a thermal screen and passive solar thermal water storage. These strategies were evaluated separately and in combination. Their effect on average greenhouse air temperature and overnight temperatures was predicted.

Overall, the simulations show that low cost and appropriate changes to increase overnight and daily average temperatures in winter could be made to the existing design. The simulations indicate that the single most promising change is the inclusion of solar passive water storage collectors or ‘solar sleeves’ between the crop rows. The model predicts that these solar sleeves would raise the average greenhouse air temperature by 2.6°C and the overnight air temperature would be increased by 4.2°C. However, this benefit would be achieved at the expense of crop production area within the greenhouse.

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