Title

Modified solar insolation as an agronomic factor in terraced environments

Journal

Land Degradation and Development, 11(3)

ISSN

1085-3278

Authors

Evans, TP
Winterhalder, B

Publication Date

2000-05-01

DOI

10.1002/1099-145x(200005/06)11:3<273::aid-ldr384>3.0.co;2-j

Peer reviewed

LAND DEGRADATION & DEVELOPMENT

Land Degrad. Develop. **11**: 273–287 (2000)

MODIFIED SOLAR INSOLATION AS AN AGRONOMIC FACTOR IN TERRACED ENVIRONMENTS

T. P. EVANS*[1] AND B. WINTERHALDER[2]

[1]*Department of Geography and Center for the Study of Institutions, Population and Environmental Change, Indiana University, Bloomington, Indiana, USA*

[2]*Department of Anthropology and Curriculum in Ecology, University of North Carolina at Chapel Hill, North Carolina, USA*

Received 15 August 1998; Accepted 16 August 1999

ABSTRACT

We present a model that calculates incident solar radiation falling on terraced and unterraced fields in steep slope environments. The results are presented as a function of altitude, latitude, slope aspect, slope angle, and season. The net solar benefit or cost from slope leveling (terracing) differs significantly according to these situational factors. For instance, terracing will confer a net direct solar radiation benefit of 15 per cent on south-facing 30-degree slopes at the Equator for a typical growing season; it will reduce net annual direct solar receipt by 21 per cent on south-facing 30-degree slopes at 45° N latitude. Modified solar radiation must be considered as potentially important in the historical origins, functioning and abandonment of terracing. It should be a component in agronomic evaluation of modern terrace construction, restoration, or maintenance.

KEY WORDS: terraces; solar radiation; topography; agriculture

INTRODUCTION

Agricultural Terracing

Terracing is an intensive, widespread, and effective means by which humans have modified slopes in order to pursue agriculture on otherwise uncultivatable hillslopes, reduce soil erosion, and improve crop productivity. It is an anthropogenic landscape feature found throughout the tropical and low-latitude temperate regions (Perry, 1916). Studies have located terraces in the New World (Donkin, 1979) and Latin America (Williams, 1990; Treacy and Denevan, 1994), as well as New Mexico (Sandor *et al.*, 1990), Mexico (Smith and Price, 1994), Yemen (Vogel, 1987, 1988; Varisco, 1991), Lebanon (Zurayk, 1994), Nepal (Johnson *et al.*, 1982), China (Xing-guang and Lin, 1991; Veeck *et al.*, 1995), the Mediterranean (Treacy and Denevan, 1994), and Europe (Treacy and Denevan, 1994). Few reliable inventories of the extent of agricultural terracing are available, but selected estimates suggest the impressive scale of the feature: for China, 400 000 km^2 (Xing-guang and Lin, 1991: 198); for Peru 500 000 ha (Denevan, 1988).

Terracing can range from unintentional slope leveling due to natural processes of erosion and accumulation against balks or hedgerows to the highly visible and sophisticated public works projects of ancient empires (e.g. Donkin, 1979). The former may have been incidental; the latter obviously follow from sophisticated engineering and draw on large labor and capital inputs. The literature on terracing is small relative to its agroecological importance (Treacy and Denevan, 1994) and it is multidisciplinary, scattered among the disciplines of archaeology, geography, and agronomy.

Despite widespread contemporary use, in most regions terraces originated in antiquity. We have been unable to locate documentation of extensive modern construction of terraces. This historical distance

---

*Corresponding author: Prof. Tom Evans, Department of Geography and Center for the Study of Institutions, Population and Environmental Change, Student Building 120, Indiana University, Bloomington, IN 47405, USA. E-mail: evans@indiana.edu inspires a variety of questions: When and how were terraces constructed (or if unintentional, when and how did they develop)? By whom? What agroecological functions were they designed to serve? What functions might they serve as an incidental (unintended) result of their design? How costly are they? What agroecological conditions affect their distribution and form? How productive and sustainable are they as an agricultural substrate? Why has much agricultural terracing of the world been at least partially abandoned, and under what conditions would it now be feasible to reclaim or extend agricultural land using terracing?

The last question is one of increasing contemporary importance: although most extant terracing has prehistoric origins (Hilsum, 1987), a future of increasing population and overworked agricultural land, along with a desire to avoid the harmful consequences foreseen as extensive areas of abandoned terraces deteriorate and collapse, has impelled renewed attention to the possibility of restoring and/or constructing new terraces (e.g. de la Torre and Burga, 1986; Johnson *et al.*, 1982; Treacy, 1987, 1989; Vogel, 1987; Zurayk, 1994; Veeck *et al.*, 1995).

Researchers have reported substantial terrace abandonment (50–60 per cent) in Peru[1] (Denevan, 1988) and similar estimates have been reported in Chile (Wright, 1963: 73). While Donkin (1979: 35) suggests that the total percentage of terraces abandoned in Central and South America is closer to one-third, this still represents a substantial amount of field surface. Possible causes of abandonment include demographic, social and biophysical factors. Population decrease (disease, out-migration), loss of irrigation management skills, and climate changes have been hypothesized to be responsible for terrace abandonment (Donkin, 1979; Treacy, 1989). Scientific researchers and government-funded organizations have supported the reconstruction of abandoned terraces because of their agroecological benefits (Treacy, 1989; Zurayk, 1994). However, terrace reconstruction can require nearly as much labor investment as the initial terrace construction (Treacy and Denevan, 1994: 103). Despite this substantial cost, terrace reconstruction remains a viable means of reducing the fragility of steep-slope environments. Given this context, it is important to understand the agronomic conditions under which terracing is most beneficial.

We propose that modified solar exposure – a key component of agricultural productivity – is among the significant effects of terracing. We analyze how latitude, slope angle, slope aspect, altitude and season control the degree to which modified solar insolation may represent a net benefit or cost as a result of terracing a hillslope. We demonstrate that changes in incident radiation must be considered when seeking answers to questions such as those stated above.

Terrace Functions or Benefits

Terraces convert non-arable land to arable land on slopes otherwise too steep to cultivate. They also may be used to improve the agricultural potential of slopes that could be cultivated without leveling (Wadsworth and Swetnam, 1998). In either case, scholars have proposed that by default or design terraces achieve a variety of agricultural benefits. Terraces may: (1) stabilize slopes to facilitate construction and maintenance of contour irrigation canals (Ortloff, 1988) or to reduce landslide hazards to agriculture, roads, and settlements (Johnson *et al.*, 1982); (2) reduce runoff velocity and thereby lessen soil erosion while increasing moisture retention (Spencer and Hale, 1961; Sandor, *et al.*, 1990; Williams, 1990; Smith and Price, 1994: 175; Vogel, 1987, 1988; Zurayk, 1994); (3) level the planting surface (Smith and Price, 1994: 175); (4) create better or deeper, soils (Spencer and Hale, 1961; Sandor *et al.*, 1990); or, (5) favorably modify microclimate (Treacy, 1989).

Treacy and Denevan categorize such benefits as primary, secondary, or epiphenomenal. They argue that cultivators need not have been explicitly aware of these individual functions to none the less appreciate a 'sense of overall agronomic advantage that terracing provides' (1994: 95). According to Treacy and Denevan, most observers suggest that moisture management was a widespread primary rationale for the construction of terraces. Soil development may have been primary in some cases. Although erosion control strikes modern

---

[1] Masson (1986) originally reported 75 per cent abandonment in Peru, but this estimate was revised to 50 per cent in Denevan (1988: 28). Denevan (1988) reported 61 per cent of terraces were abandoned in the Colca Valley of Peru based on aerial photography.

observers as important, most sources suggest that it was probably a secondary factor in the origin of terracing. Microclimatic modifications are most often cited as secondary or epiphenomenal factors.

While terraces may also have served social, political or military functions, most of the geographical and archaeological literature has focused on their more utilitarian agricultural advantages. Actual empirical or experimental study of these functions has been rare. We note also that researchers seldom have considered the *costs* of terrace cultivation, such as reduction in potential surface area of a leveled field or the maintenance of terrace walls (see Wadsworth and Swetnam, 1998 for an exception). Apart from the work of Earls (1986), solar radiation effects, the focus of this paper, have been mentioned in passing in only a few of the sources of which we are aware.

A Solar Radiation Hypothesis

By modifying surface orientation and the distribution of shadows, terracing changes the exposure of crops to sunlight relative to that on an unmodified slope. Terracing potentially modifies the duration, evenness, intensity, and cumulative total solar insolation available to plants. Through direct effects on photosynthesis and indirect effects on such agronomic variables as soil temperature, soil moisture, and evapotranspiration, we expect this to influence crop productivity. The direction (positive or negative) and the magnitude of the effect of terracing on direct solar radiation will be determined by surface slope, exposure, latitude, altitude, season, time of day, local atmospheric conditions such as daily distributions of cloudiness and reflectance from surrounding terrain. With the exception of atmospheric conditions and reflectance, these are the variables of our analysis.

We focus on bench, or linear contour terraces (see Treacy and Denevan, 1994: 96–101), a form that typically has the following characteristics: a somewhat inward-sloping, retaining wall of stacked stone, a level surface, a close match to slope contours, cut-and-fill construction in contiguous, serial rows, and built-in features such as irrigation, steps or niches. The regular geometry of bench terraces facilitates modeling their agroecological features.

SOLAR RADIATION ON A PLANAR SURFACE

Geometric Relationships and Constants

The intensity of direct (Brock, 1981: 8) or beam (Kreith and Kreider, 1978: 37) solar radiation per unit area (I, MJ m^{-2}) is a function of (1) the elliptical nature of the Earth's orbit, (2) the solar constant, (3) the solar incidence angle (i), (4) daylength (sunrise–sunset), and (5) solar attenuation through the atmosphere. We discuss each in turn.

A radius vector correction (R), applied to the solar constant to allow for a 3 percent eccentricity in the Earth's orbit. This correction varies between 0·9832 and 1·0167 (Brock, 1981: 4). This correction factor was estimated using:

$$R = 1/\{1 + [0{\cdot}033 \times \cos(360d/365)]\}^{1/2}$$

The solar constant, the average radiation intensity at the top of the atmosphere, is 1367 W m^{-2} (Wehrli, 1985).

Solar incidence angle i is the angle between the perpendicular (normal) to a surface and a line parallel to the sun's rays. Solar intensity/unit area is greatest for i equal 0 degrees and least for an i approaching 90 degrees. Five variables control (i) for a planar surface (symbols and definitions follow Kreith and Kreider (1978) unless otherwise noted).

(1) *Solar hour angle* (h_s) measures the movement of the sun through the sky from sunrise to sunset. It is determined by 15 degrees times the number of hours before or after the local solar noon, with a

convention of negative morning and positive afternoon values. Given the time from midnight (T), the solar hour angle may be computed using

$$h_s = (T - 12) \times 15$$

(2) *Solar declination* (δ_s) is the latitude where the sun is directly overhead and derives from the tilt of the Earth's axis relative to its orbital plane around the sun; it is the factor responsible for northern and southern hemisphere seasonality. From a northern hemisphere perspective, it varies annually from 23·45° N latitude at the summer solstice to 23·45° S latitude at the winter solstice. Declination is determined relative to Julian days (d), numbered consecutively from 1 January to 31 December (e.g. the summer solstice is day number 173). Declination may be estimated using the following equation:

$$\delta_s = 23{\cdot}45 \times \sin[360(284 + d)/365]$$

(3) *Latitude* (L) is measured in degrees, positive north of the Equator and negative south.
(4) *Slope aspect, or surface azimuth angle* (a_w) is the angle on a horizontal plane between due south and the projection onto that plane of a horizontal line tangent to a surface. It is measured in degrees (0 degrees–360 degrees) beginning from due north.
(5) *Slope, or surface tilt angle* (β) is the angle between the surface of interest and a horizontal plane. It is measured in degrees, from 0 to 90 degrees.

The first three of these angles (h_s, δ_s, and L) determine the geometry of the solar position in the sky relative to a horizontal plane on the Earth's surface. The second two variables (a_w, β) establish the orientation of a planar surface relative to that horizontal. Given values for these variables, incidence angle is established by

$$\begin{aligned}\cos(i) = {} & \sin\delta_s\,(\sin L\ \cos\beta - \cos L\ \sin\beta\ \cos a_w)\\ & + \cos\delta_s\ \cos h_s\ (\cos L\ \cos\beta + \sin L\ \sin\beta\ \cos a_w)\\ & + \cos\delta_s\ \sin\beta\ \sin a_w \sin h_s\end{aligned}$$

Simpler equations may be used to determine incidence angle for cases restricted to either flat south-facing, or non-south-facing surfaces, but the above formulation is able to model all situations (Kreith and Kreider, 1978).

Daylength. Following Kreith and Kreider (1978: 60; italics in original), 'The sun is said to rise and set on a surface, either *when the surface-incidence angle is 90 degrees* or *when the altitude angle is zero*, whichever occurs closer to solar noon'. An incidence angle greater than 90 degrees on a tilted surface implies that the sun is behind the surface; an altitude angle less than 0 degrees implies that the sun is below the horizon.

Atmospheric transmittance also affects incident radiation. Altitude and solar elevation angle (the angle between local horizontal plain and center of sun; complement of *zenith angle*) determine the degree to which incident radiation is diminished by passage through the atmosphere (Kreith and Kreider, 1978). Except for turbidity, this 'atmospheric extinction' is controlled by the relative air mass (Brock, 1981: 8) through which direct beam radiation must pass. Thus, transmissivity is characterized by an inverted 'U' with a flattened peak: it is very low in the early morning and late evening hours but rises quickly to a flattened peak through the mid-day. The formula of Kreith and Kreider (1978: 43) gives the values shown in Table I (calculated for two altitudes, sea-level and the approximate upper limit of agriculture in the Andes, 4000 m).

We will show that atmospheric transmissivity has an important impact on the solar capture of terraced surfaces and non-terraced surfaces.

Terrace Morphology and Solar Radiation Reception

Figure 1 depicts schematically the effect of terracing in the simple circumstance of a single steep mountain ridge (30-degree slope), oriented north–south and rising from a plain located on the Equator. We observe it

Table I. Atmospheric transmissivity as a function of time of day and altitude

Time of day	Atmospheric transmissivity	
	Sea-level	4000 m
6:30	0·25	0·36
7:00	0·39	0·51
8:00	0·55	0·68
9:00	0·63	0·74
10:00	0·68	0·79
11:00	0·71	0·81
12:00	0·72	0·81

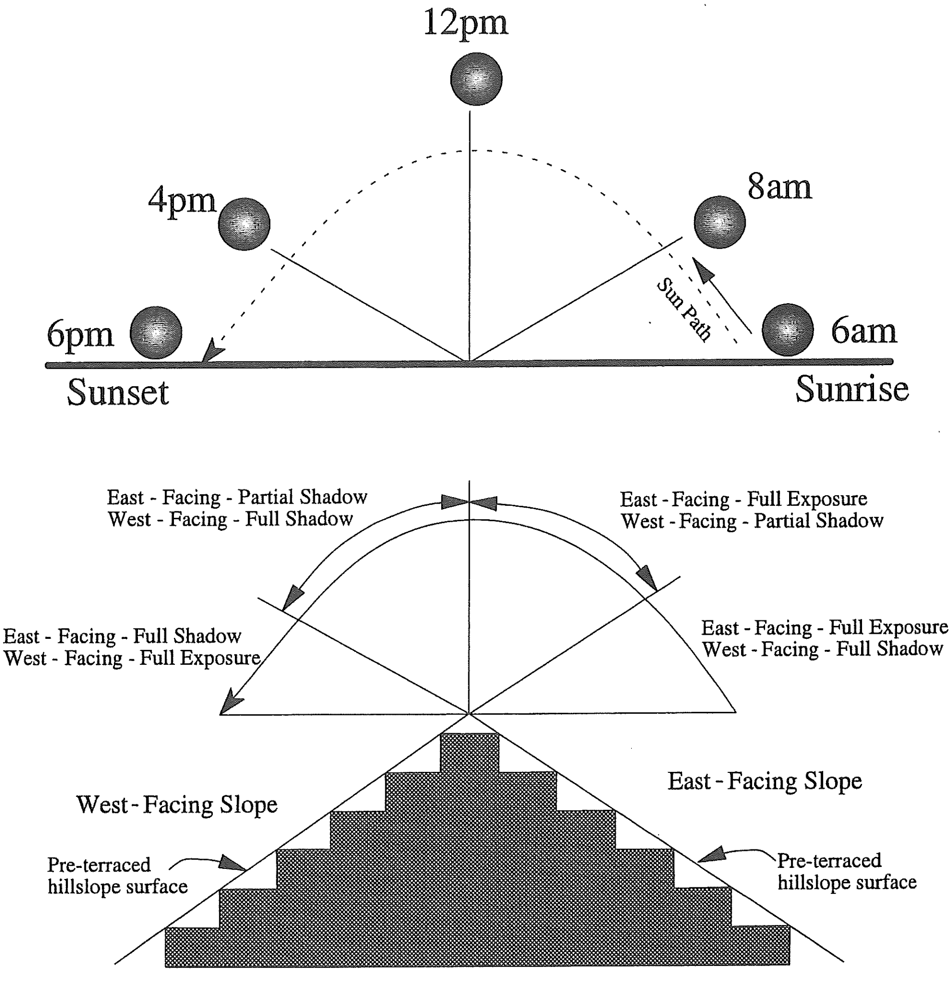

Figure 1. Solar exposure on east–west-facing 30-degree slope, spring equinox.

on the date of the solar equinox (JD 80 or 265). At the moment of sunrise on the north–south ridge, beam radiation is parallel to the terrace surface but strikes the eastern slope at an incidence angle of 60 degrees. As the sun passes through the sky the entire terrace surface is exposed until noon at which time the upslope terrace wall begins to shade a portion of the terrace. Terrace platforms will be in increasing shadow from noon until the hour angle at which both the eastern slope and terraces enter full shadow (4 p.m. in this case). The incidence angle on the slope is lowest at mid-morning (reaching 0 degrees at 10 a.m.); on the terrace surface it is lowest at noon. The opposite sequence of exposure conditions will affect the west-facing slope and terraces.

Because of shading from upslope terrace walls, the duration of solar exposure on a terrace surface will be somewhat less than that on an unterraced slope for all of the platform surface except that at the extreme terrace edge or lip. However, compared to a slope, direct beam radiation will strike the horizontal terrace surface at a lower incidence angle during the mid-day periods when it is least attenuated by atmospheric transmissivity. The balance of these effects – relative incidence angle, shading, and transmissivity – will determine whether solar capture is greater on the leveled terrace surface than on the underlying slope.

If we reposition our imaginary ridge to an east–west orientation, parallel to the Equator, then it is apparent that both slope and terrace platform will receive insolation over all of their surface for an equal duration of time. So long as the path of the sun is directly over the ridgeline through the day, there will be no microtopographic shadowing. Insolation intensity will be the same on both the north- and south-facing slopes. Solar exposure will be longer than in the north–south case, as sunrise and sunset will correspond to 6 a.m. and 6 p.m. on both faces. Again solar incidence angles will be lower on terraced surfaces during the mid-day period when atmospheric transmissivity is highest. Without the complicating factor of shadows, it is evident that terraces will have greater total daily solar radiation/unit area (total daily solar radiation, TDSR) than the slope.

As the latitude of this imagined east–west ridge shifts northward relative to the noon-time position (declination) of the sun, the platform-to-slope advantage diminishes on the south face, and it may grow on the north face, albeit in a manner complicated by shading.

This simple schematic suggests several hypotheses.

(1) Other things equal, leveled (terraced) surfaces will have higher total solar insolation due to their having lower incidence angles during the mid-day period when direct beam transmissivity through the atmosphere is greatest.

(2) The relative advantages of the effect cited in (1) will diminish with altitude and will increase with slope angle;

(3) Terracing cannot expand the duration of solar exposure relative to the underlying slope. However, surfaces (terraced or not) on east–west trending ridges will be in sunlight for longer periods than surfaces on north–south trending ridges;

(4) Microtopographic shadowing by terrace walls will have its greatest negative effect on north–south trending ridges, and on the pole-facing slope of east–west ridges for which latitude exceeds the value of solar declination.

Simplifying Assumptions

In order to produce a model of the relationships controlling relative beam radiation on terraces and slopes, we have ignored diffuse (Brock, 1981: 8) or indirect (sky) radiation, as well as that reflected from surrounding features (perhaps most importantly, from upslope terrace walls). Terrain reflected radiation can be significant in steep-slope habitats, especially if there are snow or ice-covered surfaces (Duguay, 1993). We also ignore horizon screening (Duguay, 1993: 344) by surrounding relief. 'Unfortunately, radiation transfers in mountainous terrain are extremely complex, so precise estimates of the components of net radiation have not been forthcoming . . .' (Duguay, 1993: 340). However, it can be noted that diffuse radiation reception at the surface is typically proportionally higher relative to direct radiation when transmissivity is low (Oke, 1987: 27). Therefore, in areas where there is substantial morning fog, cloudiness, or haziness, diffuse radiation is expected to have a more substantial impact on the total solar radiation reception at the surface.

We assume that terrace walls (risers) are vertical and field surfaces are level. We ignore such 'edge effects' as the uppermost terrace surface on a ridge, or shading induced by walls or other structures located at the end of a linear row of terraces. During the period in which a platform surface is in partial shadow (Figure 1), we average the intensity of solar radiation over the whole surface, rather than calculate it as an expanding band of shadow that moves from the foot of the ascending riser to the lip of the descending wall. This is artificial from the perspective of potential intra-terrace differences in productivity (plants at the lip will receive more direct-beam radiation) but is consistent with our effort to assess average agricultural production for the terrace surface as a whole relative to slopes. Geometrically, we have calculated the effect of shading by subtracting the radiation striking the back of the terrace wall from that which would have fallen on the terrace surface were no wall present.

Simulation runs were performed using a C program called SOLARCAL. User-defined inputs include: latitude, Julian date, time of day, slope, aspect, and altitude. SOLARCAL allows insolation to be calculated for a fixed set of parametric conditions, or accumulated by incrementing specific variables or sets of variables. Thus, solar insolation can be determined for a specific time like noon, or accumulated from sunrise to sunset, or from JD 120 to 240.

RESULTS

Latitude, Slope Angle, Slope Aspect, and Atmospheric Transmissivity

Table II shows beam radiation intensity accumulated for one day on terraced and unterraced north–south and east–west facing slopes at the solar equinox. On an east–west-facing ridge with a 30-degree slope (equinox, at the top of the atmosphere, i.e. no transmissivity effects), the solar incidence angle is 60 degrees at sunrise. Solar insolation is greatest on the slope at 10 a.m., when the incidence angle equals 0 degrees. Terrace insolation first exceeds that which would fall onto the unterraced slope at 11 a.m.; it peaks at noon ($i = 0$ degrees), and thereafter drops due both to increasing incidence angle and to shadowing. Slope insolation is more intense during the early-morning hours; terrace insolation from late morning to sundown at 4 p.m. Total solar daily value on the terrace (29·35 MJ day^{-1}) is 84·4 per cent of that on the slope (34·78 MJ day^{-1}). At sea-level (transmissivity effects added) the terrace value is 19·43 MJ day^{-1}; the slope value is 21·45 MJ day^{-1}. Atmospheric attenuation considerably reduces total daily insolation (by 33·8 per cent for terrace surface; 38·3 per cent for the slope) and it narrows the gap between these features. At sea-level terraces receive 90·6 per cent of the insolation falling on the 30-degree slope. Diminished transmissivity in the early morning attenuates the advantage to slopes of relatively low incidence angle during this portion of the day.

The values for a north–south-facing ridge are also shown in Table II. This aspect reverses the advantages. Without atmospheric attenuation, terrace insolation (36·97 MJ day^{-1}) exceeds that on the slope (32·02 MJ day^{-1}) by 15·5 per cent. With transmissivity both terraces (23·85 MJ day^{-1}) and slopes (20·65 MJ day^{-1}) receive less cumulative solar radiation, but the terrace advantage is unchanged at 15·5 per cent. This is expected from the geometry of the situation. Solar attenuation is distributed symmetrically on the slope and terrace throughout the photoperiod.

Total solar insolation for north–south-facing terraces exceeds that for east–west-facing (by 26·0 per cent, whether with or without transmissivity). For slopes (unterraced surfaces) the situation is reversed. Despite

Table II. Total daily solar insolation (MJ day^{-1})

Position	Terraced (MJ)	Non-terraced (MJ)	Ratio (terr/non-terr)
East–west-facing – top of atmosphere	29·35	34·78	0·84
East–west-facing – sea-level	19·43	21·45	0·91
North–south-facing – top of atmosphere	36·97	32·02	1·16
North–south-facing – sea-level	23·85	20·65	1·16
30° N latitude north-facing; sea-level	12·88	11·16	1·15
30° N latitude south-facing; sea-level	19·54	22·69	0·86

being in shadow for part of the photoperiod, the low mid-morning incidence angles on east–west-facing slopes give them a modest advantage of between 8·6 per cent (without attenuation) and 3·9 per cent (with attenuation).

Now consider the situation in which we move our north–south-facing slopes to 30° N latitude (all else equal). On the north-facing slope terraces (12·88 MJ day^{-1}) get 115·4 per cent the solar radiation of the slope (11·16 MJ day^{-1}). The south-facing slope has higher values in both categories, but terraces (19·54 MJ day^{-1}) receive only 86·1 per cent the TSI of the slope (22·69 MJ day^{-1}). These values characterize the two equinox days of the year.

Solar Radiation Accumulated by Growing Season and Calendar Year

The following section compares terraced and non-terraced solar radiation estimates for a variety of positional and seasonal scenarios in the northern hemisphere. Figures 2a–g show solar insolation estimates by aspect, for latitudes 0–45 in 7·5° increments, for a slope of 15 degrees. Solar insolation was accumulated for a typical growing season of 120 days (starting with solar day 120, ending with solar day 240). The length, start date, and end date of the growing season were chosen to include the period of the year when solar radiation reception is at an annual peak in the northern hemisphere and during which agricultural production is focused in mid-latitudes. These figures show how any advantage or disadvantage of terracing is heavily dependent on aspect. The magnitude of the advantage or disadvantage is dependent on latitude, all other factors remaining equal. In these estimates, the solar insolation for terraced slopes is slightly underestimated because these models do not account for reflection of direct solar radiation from adjacent terrace walls.

Tables III–VI show the ratio of direct solar radiation reception on terraced surfaces to non-terraced (sloped) surfaces for a variety of combinations of aspect, latitude, and slope (pre-terraced). Tables 3 and 4 show these ratios compared for values accumulated over an entire year. Tables V and VI show these ratios compared for values accumulated for a typical growing season in the northern hemisphere (Julian date 120–240). Examination of these tables shows that the cost or benefit of terracing a slope is a function of (1) pre-terraced slope angle, (2) latitude, (3) aspect, and (4) day of the year.

In general, the benefit of terracing to TDSR is modest, or in some cases a net disadvantage. However, in certain cases, terraced surfaces receive substantially more solar radiation than non-terraced surfaces. The greatest benefit of terracing is seen at low to mid-latitudes on 30-degree slopes whose aspect faces the Equator when radiation is accumulated for a typical growing season. Terraced 30-degree slopes receive 115 per cent that of non-terraced slopes on south-facing slopes in the Northern hemisphere and north-facing slopes in the Southern hemisphere. Accordingly, we see a benefit for 30-degree slopes facing away from the Equator for mid-to-high latitudes (terraced slopes 110–111 per cent of non-terraced slopes). For these same

Table III. Ratio of terrace radiation reception to slope radiation reception, accumulated through 365 day year, hill slope angle = 15 degrees

Aspect (degrees)	Latitude (degrees)						
	0	7·5	15	22·5	30	37·5	45
North (−180)	0·98	1·00	1·01	1·02	1·02	1·03	1·03
Northeast (−135)	0·96	0·96	0·97	0·98	0·98	0·98	0·98
East (−90)	0·93	0·93	0·93	0·92	0·92	0·91	0·90
Southeast (−45)	0·95	0·94	0·93	0·92	0·90	0·88	0·86
South (0)	0·99	0·97	0·95	0·93	0·91	0·88	0·85
Southwest (45)	0·96	0·95	0·93	0·92	0·90	0·88	0·86
West (90)	0·93	0·93	0·93	0·92	0·92	0·91	0·90
Northwest (135)	0·95	0·96	0·97	0·97	0·97	0·97	0·97

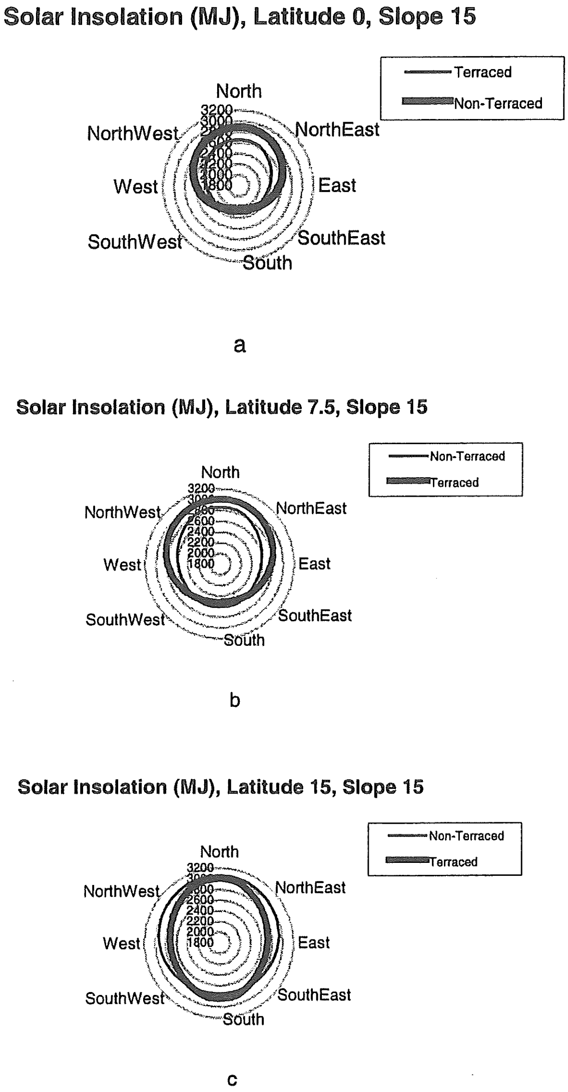

Figure 2(a,b and c).

slopes, when solar radiation is aggregated over an entire year, the benefit is somewhat less, but the benefit is still substantial, particularly for slopes facing away from the Equator at high latitudes (terraced slopes 112 per cent of non-terraced slopes for north-facing Northern hemisphere slopes and south-facing Southern hemisphere slopes).

This same pattern holds under the same conditions on 15-degree slopes, but the proportional differences between terraced and non-terraced surfaces are less. In other words, the difference between terraced and non-terraced slopes is greatest when the slope angle is high. For 30-degree slopes, direct solar radiation reception on terraced slopes ranges between 79 per cent and 115 per cent that of non-terraced slopes. For 15-degree slopes, this same range is 85 per cent to 104 per cent.

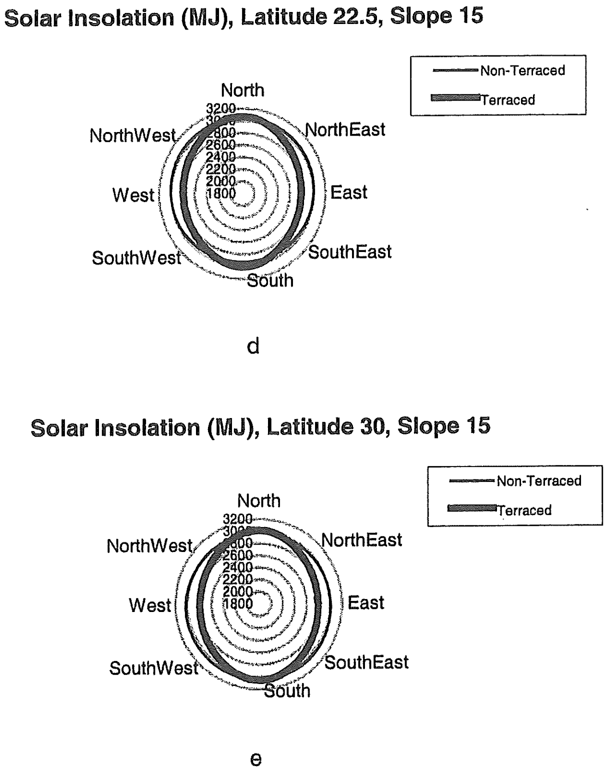

Figure 2(d and e).

Table IV. Ratio of terrace radiation reception to slope radiation reception, accumulated through 365 day year, hill slope angle = 30 degrees

Aspect (degrees)	Latitude (degrees)						
	0	7·5	15	22·5	30	37·5	45
North (−180)	1·03	1·06	1·09	1·11	1·12	1·12	1·12
Northeast (−135)	0·97	0·98	0·99	1·00	1·01	1·00	1·00
East (−90)	0·91	0·90	0·90	0·89	0·88	0·87	0·85
Southeast (−45)	0·96	0·94	0·92	0·89	0·86	0·83	0·79
South (0)	1·03	1·00	0·97	0·93	0·88	0·83	0·79
Southwest (45)	0·97	0·95	0·92	0·89	0·86	0·83	0·79
West (90)	0·91	0·90	0·90	0·89	0·88	0·86	0·84
Northwest (135)	0·96	0·98	0·99	0·99	1·00	0·99	0·98

DISCUSSION

Benefits, Costs and Functionality

Terracing is often given a functional interpretation that cites benefits but ignores the costs or trade-offs entailed in landscape modification (Williams (1990) is an exception). For example, terracing of shallow slopes may improve unit-area agricultural productivity by leveling, but it thereby diminishes the area available for planting. Few studies mentioning the benefits of a more horizontal surface have allowed for the fact that terracing reduces the total area of cultivation (see Wadsworth and Swetnam (1998) for an

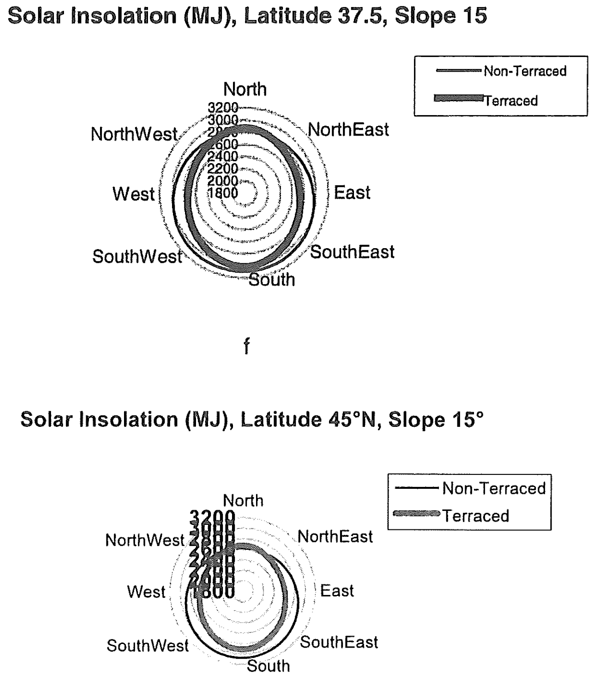

Figure 2(f and g).

Figure 2(a–g). Solar insolation estimates by aspect, for latitudes 0–45 in 7·5° increments.

Table V. Ratio of terrace radiation reception to slope radiation reception, accumulated through 120 day growing season, hill slope angle = 15 degrees

Aspect (degrees)	Latitude (degrees)						
	0	7·5	15	22·5	30	37·5	45
North (−180)	0·92	0·95	0·98	1·00	1·01	1·02	1·02
Northeast (−135)	0·92	0·93	0·94	0·95	0·96	0·97	0·97
East (−90)	0·93	0·93	0·93	0·93	0·93	0·92	0·92
Southeast (−45)	0·99	0·99	0·98	0·97	0·95	0·94	0·92
South (0)	1·04	1·04	1·03	1·03	1·00	0·97	0·95
Southwest (45)	1·00	0·99	0·98	0·97	0·95	0·94	0·92
West (90)	0·93	0·93	0·93	0·93	0·92	0·92	0·91
Northwest (135)	0·92	0·93	0·94	0·95	0·96	0·96	0·96

exception). Construction and maintenance represent investments that must be amortized against increased or more sustainable productivity. Likewise, as shown here, terracing effects on solar radiation might be positive or negative to varying degrees which can be predicted using such factors as latitude, aspect, and slope. Models and empirical studies that take account of both costs and benefits are needed to describe the human-environment relationships in these systems and to evaluate the sustainability of terracing under different conditions.

Table VI. Ratio of terrace radiation reception to slope radiation reception, accumulated through 120 day growing season, hill slope angle = 30 degrees

Aspect (degrees)	Latitude (degrees)						
	0	7·5	15	22·5	30	37·5	45
North (−180)	0·90	0·97	1·03	1·08	1·10	1·11	1·11
Northeast (−135)	0·90	0·92	0·95	0·96	0·98	0·98	0·99
East (−90)	0·91	0·91	0·91	0·91	0·90	0·89	0·88
Southeast (−45)	1·05	1·03	1·01	0·99	0·96	0·93	0·89
South (0)	1·15	1·15	1·15	1·13	1·08	1·02	0·96
Southwest (45)	1·06	1·04	1·02	0·99	0·96	0·93	0·89
West (90)	0·91	0·91	0·91	0·90	0·90	0·88	0·87
Northwest (135)	0·89	0·92	0·94	0·96	0·97	0·97	0·96

We hypothesize that, whether positive or negative, solar radiation effects are secondary or epiphenomenal considerations in the origin and design of extant terracing (although not thereby unimportant to the origins and development of terraces). Solar radiation may have played a more important role in the selective abandonment of terraces as lower yielding terraces would likely be the first to be abandoned. As a matter of applied agroengineering, consideration of solar radiation could be important in the design of new terracing or recovery of abandoned terraces.

Solar Insolation and Plant Productivity

Terracing of steep slope habitats modifies the duration, evenness, and absolute amount of solar insolation per unit area of ground surface. In general, agronomic studies provide good reasons to think that the timing and intensity of irradiance on terraces relative to that on slopes will have corresponding effects on crop growth and productivity. The effect of solar radiation on soil temperature and moisture during seed germination and seedling stages may be particularly important to the productivity of a terraced field. However, this has not been shown experimentally. Under natural conditions, agricultural productivity is also determined by factors such as temperature, soil moisture, vapor pressure, disease, nutrients, competition, and herbivore infestations (see Demetriades-Shah *et al.*, 1992: 197; Arkebauer *et al.*, 1994; Kiniry, 1994: 229).

Ecological studies have examined the relationship between topography (e.g. elevation, slope angle, and slope aspect), solar radiation, and vegetation primarily in natural environments (Holland and Steyn, 1975; Kirkpatrick and Nunez, 1980; Davis and Goetz, 1990; Dubayah, 1994). Solar radiation has a key role:

> '... subtle variation in solar radiation can lead to changes in soil temperature and moisture, and the surface-atmosphere temperature and moisture gradients, which in turn may affect stomatal, canopy and surface conductances, creating a complex interaction between the soil, atmosphere and vegetation'. (Dubayah, 1994: 627)

Solar radiation also affects soil chemical properties and edaphic development (Kutiel, 1992). We expect these same processes to be at work in topographically complex agricultural settings such as terracing.

In a review of the agronomic literature, Spitters (1990: 351) states that 'It is general experience that, under favourable growth conditions, the growth rate of a crop is proportional to the amount of light it intercepts' (Spitters, 1990: 351). While this may appear to contradict the (non-linear) leaf saturation effect (see Aikman, 1989), experimental evidence shows that 'in a canopy, most of the leaves are for the greater part of the day photosynthesizing at non-saturating intensities' (Spitters, 1990: 358). Kiniry (1994: 229) and Monteith (1994: 217) concur: under field conditions, there is typically a linear response between biomass growth and interception of radiation energy. More rapid growth results in greater accumulation of mass, possibly greater yields of edible portions, and less chance of late-season damage from frost.

Taking a specific example, Aikman (1989: 862; see also Markov, 1993) suggests that greenhouse orientation of row crops like tomatoes be shifted from north–south to east–west, in order to achieve more uniform foliage irradiance and higher yields. The rationale for this proposal is geometrically analogous to the insolation gain we find in our comparison between terraces on north–south- and east–west-oriented mountain slopes. Aikman's (1989) review covers theoretical predictions and experimental evidence showing that the magnitude of such redistribution is great enough to have significant practical consequences. In controlled light cabinets, Aikman (1989) manipulated radiation distribution over the photoperiod, exposing tomato plants to three regimes of equal total solar insolation: high–low (high intensity for half the photoperiod followed by low intensity), low–high, and, average intensity for the whole photoperiod. The uniform lighting regime produced plants with 33 percent greater dry weight.

The relationships between modified solar exposure on terraces (compared to slopes) and agricultural productivity is likely to be multivariate and complex. Agronomic benefits due to increased photosynthesis as a result of increased direct solar radiation reception may be offset by increased evapotranspiration and an associated moisture deficit in moisture limiting environments. We have cited these specific examples of analogous relationships to indicate that practical consequences are of great enough likelihood and magnitude to bear experimental investigation in field settings.

Simplifying Assumptions Revisited

Several of our simplifying assumptions bear revisiting. For instance, we have ignored atmospheric effects, except for transmissivity resulting from altitude and solar altitude angle. Other interesting transmissivity interactions are possible. Regular early-morning or late-afternoon cloudiness during the cropping season would enhance the solar benefit of terracing; mid-day cloudiness would diminish it.

Similarly, we have not taken account of reflected radiation, and thus do not know the potential contribution of reflectance from the terrace face (as a function of texture and albedo). Including reflected radiation from surrounding surfaces in the model would benefit terraced surfaces more than non-terraced surfaces because the vertical walls of adjacent terraces would proportionately reflect more radiation to surrounding fields and less back to the atmosphere. Non-terraced surfaces are at an angle more normal to the angle of insolation. If geometric relationships make wall reflectance a significant source of photosynthetically active radiation, it might be possible to artificially enhance solar capture by placing reflecting materials on the surface of the riser (as in greenhouse production; see Aikman, 1989).

This model has focused on short-wave radiation and has not simulated the affect of long-wave radiation either from the atmosphere or surrounding landscape features. Models of net radiation in mountainous terrain are highly complex (Duguay, 1993: 340) and the construction of such a model has not been attempted here. However, it is possible that long-wave radiation from terrace walls is another agronomic benefit of terracing, particularly where terrace walls absorb substantial amounts of radiation during the day. This long-wave may be particularly important in relation to frost risk. Valley floors accumulate cold air drained from higher altitudes, and valley slopes may be warmer than valley floors in contrast to the adiabatic lapse rate (Geiger, 1969). Cold air glides over terraced slopes and settles in the valley floor, and Treacy and Denevan (1994) reported that terrace slopes are 1–2°C warmer than valley floors. Long-wave radiation from terrace walls is likely to be an additional factor contributing to the abatement of frost risk on terraced valley slopes, although the specific affect is not quantified here.

Our model also averaged-out the distribution of shadows on a terrace surface. In practice, these may offer a means of testing insolation effects. Shadows appear first at the back of a north–south trending terrace surface and advance with solar hour angle toward its lip. Assuming that thermal, moisture and other conditions are the same or can be controlled, plants near the back of the plot should have lesser biomass than those set near the lip as a result of this differential insolation.

Two stages of plant development are particularly influenced by solar insolation. During seed germination and seedling growth there is little vegetative cover on the surface. Soil temperature is directly affected by solar absorbed insolation as a function of surface aspect. Solar insolation is increasingly intercepted by vegetative cover as plants develop above-ground biomass. As crops develop their photosynthetic layer, the plant canopy for some crops may assume a different and more complex morphology and are affected by factors such as inter-plant shadowing (see Dubayah, 1994: 638). Demetriades-Shah *et al.* (1992) suggest that, while sunlight is clearly an important component of plant growth, it is not always a limiting factor and suggest that too much importance is placed on solar radiation reception. Alternatively, Kiniry (1994: 229) and Monteith (1994: 217) report that the response between solar insolation and plant growth is linear. Terracing alters the number of hours of exposure to sunlight and this difference is probably of greater importance than surface aspect during this stage of plant growth.

CONCLUSIONS

The SOLARCAL model shows that a terraced hillslope receives a significantly different amount of direct solar radiation compared to an unterraced hillslope. This difference is a function of latitude, slope aspect, slope angle, and seasonality. South-facing slopes at low latitudes receive the greatest benefit from terracing, while east- and west-facing slopes see the greatest net cost. This net cost is in partly due to the reduced daily exposure to sunlight on terraces as a result of shadowing from upslope terraces.

Researchers have examined terrace environments to determine the viability of reconstructing abandoned terraces and constructing new terraces in areas of moderate and steep topography. Terracing has been shown to reduce soil erosion and improve moisture retention while reducing the total surface area of a hillslope. We suggest that a modification in the direct solar radiation reception is among the significant agronomic factors associated with agricultural terracing. We do not see modified insolation as a primary incentive or conscious reason for agriculturalists to terrace historically. None the less, it should be an important element in the evaluation of terracing in steep slope environments. Terrace reconstruction requires substantial labor inputs both for the initial rebuilding of terraces and for their maintenance over time. Given the acknowledged costs of terracing, it is important to understand under what social and agronomic conditions terrace reconstruction is viable and beneficial. This research suggests that a modification in solar radiation reception is among the agronomic factors under which local-scale conditions such as slope angle and slope aspect can be used to understand optimal areas for reconstruction.

ACKNOWLEDGEMENTS

Blake Weiler provided expert programming assistance in the development of the SOLARCAL program. The research here benefited from collaboration with Sean McKnight and Jennifer DeHart at an earlier stage of this project. Scott Robeson provided valuable comments to an earlier draft of this manuscript.

REFERENCES

Aikman, D. P. 1989. 'Potential increase in photosynthetic efficiency from the redistribution of solar radiation in a crop', *Journal of Experimental Botany*, **40**, 855–864.

Arkebauer, T. J., Weiss, A., Sinclair, T. R. and Blum, A. 1994. 'In defense of radiation use efficiency: A response to Demetriades-Shah, *et al.*', *Agricultural and Forest Meteorology*, **68**, 221–227.

Brock, T. D. 1981. 'Calculating solar radiation for ecological studies', *Ecological Modelling*, **14**, 1–19.

Davis, F. W. and Goetz, S. 1990. 'Modeling vegetation pattern using digital terrain data', *Landscape Ecology*, **4**, 69–80.

de la Torre, C. and Burga, M. (eds). 1986. *Andenes y Camellones en el Perú Andino: Historia, Presente y Futuro*, Consejo Nacional de Ciencia y Tecnologia (CONCYTEC), Lima.

Demetriades-Shah, T. H., Fuchs, M., Kanemasu, E. T. and Flitcroft, I. 1992. 'A note of caution concerning the relationship between cumulated intercepted solar radiation and crop growth', *Agricultural and Forest Meteorology*, **58**, 193–207.

Denevan, W. 1988. Measurement of abandoned terracing from air photos: Colca Valley, Peru, pp. 20–30 *in* T. Martinson, A. R. Longwell and W. Denevan (eds). *Proceedings of the Conference of Latin Americanist Geographers*, Vol. 14, Lousiana State University, Baton Rouge, LA.

Donkin, R. A. 1979. *Agricultural Terracing in the Aboriginal New World*, The University of Arizona Press, Tucson, AZ.

Dubayah, R. C. 1994. 'Modeling a solar radiation topoclimatology for the Rio Grande River basin', *Journal of Vegetation Science*, **5**, 627–640.

Duguay, C. R. 1993. 'Radiation modeling in mountainous terrain: Review and status', *Mountain Research and Development*, **13**, 339–357.

Earls, J. 1986. Experimentación agrícola en el Peru Precolombino y su factibilidad de reempleo, pp. 301–330 *in* C. de la Torre and M. Burga (eds.) *Andenes y Camellones en el Perú Andino*, Consejo Nacional de Ciencia y Tecnologia (CONCYTEC), Lima.

Geiger, R. 1969. Topoclimates, pp. 105–138 *in* H. Flohn (ed.) *World Survey of Climatology*, Vol. 2, Elsevier, Amsterdam.

Hilsum, L. 1987. 'The terraces of Wollo: a report on the soil conservation programme in the Borkena catchment, Ethiopia', *Nordic Conference on Environment and Development, Ethiopia/Sweden*, **4**, 1–16.

Holland, P. G. and Steyn, D. G. 1975. 'Vegetational responses to latitudinal variations in slope angle and aspect', *Journal of Biogeography*, **2**, 179–183.

Johnson, K., Olson, E. A. and Manandhar, S. 1982. 'Environmental knowledge and response to natural hazards in mountainous Nepal', *Mountain Research and Development*, **2**, 175–188.

Kiniry, J. R. 1994. 'A note of caution concerning the paper by Demetriades-Shah, *et al.* (1992)', *Agricultural and Forest Meteorology*, **68**, 229–230.

Kirkpatrick, J. B. and Nunez, M. 1980. 'Vegetation-radiation relationships in mountainous terrain: eucalypt-dominated vegetation in the Risdon Hills, Tasmania', *Journal of Biogeography*, **7**, 197–208.

Kreith, F. and Kreider, J. F. 1978. *Principles of Solar Engineering*, 1st edn, Hemisphere, Washington, DC.

Kutiel, P. 1992. 'Slope aspect effect on soil and vegetation in a Mediterranean ecosystem', *Israel Journal of Botany*, **41**, 243–250.

Markov, I. E. 1993. 'Distribution of the solar radiation and estimation of the productivity of agroceoenoses in protected soil', *Applied Solar Energy*, **29**, 49–52.

Masson, M. L. 1986. Rehabilitación de andenes en la comunidad de San Pedro de Casta, Lima, pp. 207–216 *in* C. de la Torre and M. Burga (eds.) *Andenes y Camellones de el Perú Andino*, Consejo Nacional de Ciencia y Technologia (CONCYTEC), Lima, Peru.

Monteith, J. L. 1994. 'Validity of the correlation between intercepted radiation and biomass', *Agricultural and Forest Meteorology*, **68**, 213–220.

Oke, T. R. 1987. *Boundary Layer Climates*, Methuen, London.

Ortloff, C. R. 1988. 'Canal builders of pre-Inca Peru', *Scientific American*, **259**, 100–107.

Perry, W. J. 1916. 'VI. The geographical distribution of terraced cultivation and irrigation', *Manchester Memoirs*, **lx**, 1–25.

Sandor, J. A., Gersper, P. L. and Hawley, J. W. 1990. 'Prehistoric agricultural terraces and soils in the Mimbres area, New Mexico', *World Archaeology*, **22**, 70–86.

Smith, M. E. and Price, T. J. 1994. 'Aztec-period agricultural terraces in Morelos, Mexico: Evidence for household-level agricultural intensification', *Journal of Field Archaeology*, **21**, 169–179.

Spencer, J. E. and Hale, G. A. 1961. 'The origin, nature, and distribution of agricultural terracing', *Pacific Viewpoint*, **2**, 1–40.

Spitters, C. J. T. 1990. 'Crop growth models: Their usefulness and limitations', *Acta Horticulture*, **267**, 349–368.

Treacy, J. M. 1987. Building and rebuilding agricultural terraces in the Colca Valley of Peru, pp. 51–57, *in Yearbook: Proceedings of the Conference of Latin-Americanist Geographers*, Elsevier, Amsterdam, Vol. 13.

Treacy, J. M. 1989. Agricultural terraces in Peru's Colca Valley: Promises and problems of an ancient technology, pp. 209–229 *in* J. O. Browder (ed.) *Fragile Lands of Latin America: Strategies for Sustainable Development*, Westview Press, Boulder, CO.

Treacy, J. M. and Denevan, W. M. 1994. The creation of cultivable land through terracing, pp. 91–110 *in* N. F. Miller and K. L. Gleason (eds.) *The Archaeology of Garden and Field*, University of Pennsylvania Press, Philadelphia, PA.

Varisco, D. M. 1991. 'The future of terrace farming in Yemen: A development dilemma', *Agriculture and Human Values*, **8**, 166–172.

Veeck, G., Zhou, L. and Ling, G. 1995. 'Terrace construction and productivity on loessal soils in Zhongyang County, Shanxi Province, PRC', *Annals of the Association of American Geographers*, **85**, 450–467.

Vogel, H. 1987. 'Terrace farming in Yemen', *Journal of Soil and Water Conservation*, **42**, 18–21.

Vogel, H. 1988. 'Impoundment-type bench terracing with underground conduits in Jibal Haraz, Yemen Arab Republic', *Transactions of the Institute of British Geographers*, **13**, 29–38.

Wadsworth, R. and Swetnam, R. 1998. 'Modelling the impact of climate warming at the landscape scale: will bench terraces become economically and ecologically viable structures under changed climates?', *Agriculture, Ecosystems and Environment*, **68**, 27–39.

Wehrli, C. 1985. *Extra-terrestrial solar spectrum*, Publication No. 615, World Radiation Centre, Davos.

Williams, L. S. 1990. Agricultural terrace evolution in Latin America, pp. 82–93, *in Yearbook, Proceedings of Conference of Latin Americanist Geographers*, Elsevier, Amsterdam, Vol. 16.

Wright, A. C. S. 1963. 'The soil process and the evolution of agriculture in Northern Chile', *Pacific Viewpoint*, **4**, 65–74.

Xing-guang, W. and Lin, W. 1991. 'On the ancient terraced fields in China', *Tools and Tillage*, **6**, 191–201.

Zurayk, R. A. 1994. 'Rehabilitating the ancient terraced lands of Lebanon', *Journal of Soil and Water Conservation*, **49**, 106–112.