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ASPECT, VEGETATION COVER AND EROSION ON SEMI-ARID HILLSLOPES

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KEY WORDS

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SUMMARY

The integrated effect of aspect on clear-sky radiation can be calculated directly from latitude, local time and topographic data. Computed values are used to drive a simplified model for actual evapotranspiration and vegetation growth in semi-arid areas. It shows the contrasts which may be expected in vegetation biomass and cover, as they vary through an average year. Large north-south contrasts are forecast in a steep valley for vegetation biomass, overland flow and erosion. They reflect both the local topography and the overall climate of the area. Combining this model for water balance with an overland flow model driven by the natural or man-modified vegetation cover, forecasts are also be made about rates of sediment yield, and the resulting asymmetry in slope form which may develop. Results are compared with observed distributions for southeast Spain.

INTRODUCTION

The important role of aspect in controlling the distribution of plants and vegetation communities has long been recognised. Shreve (1922) was one of the first to quantify the influence of differences in solar radiation due to slope and aspect. He recognised the effects, acting through soil moisture and temperature, on the vegetation of the western U.S.A. Tansley and Chipps (1926) found that the most important effect of radiation contrasts, for low latitude semi-arid areas, was through differences in soil water balance which influence plant germination. For north - south contrasts in S.W. Texas, Cottle (1932) found that soils on south facing slopes were 5-11°C warmer (at 5cm depth), had 3-15% lower moisture content and 24-44% greater evaporation than soils on the north facing slopes. Boyko (1947) emphasised differences in vegetation structure for slopes in Israel, finding greater diversity on north facing and shaded slopes.

Since 1960 there has been improved data on site microclimates and improved analysis of statistical differences between vegetation communities. Ayyad and Dix (1964) found the greatest contrasts between NNE and SSW facing slopes in a study of Saskatchewan grasslands. The best statistical predictors of vegetation were found to be soil moisture and soil temperature. Position on the slope, identified with runoff, was also found to be an important determinant of soil organic matter and pH. Mayland (1972) used a measure of incident solar radiation, but found that it only accounted for 22% of the variation in plant frequency. He concluded that soil moisture, and other climatic factors were also very important. Geiger (1973) noted the principles governing the daily and seasonal variation in solar radiation received on a sloping surface. He noted that vegetation contrasts persisted into low latitudes where solar radiation contrasts are relatively weak. He attributed the effect to the timing of maximum radiation during the course of the day. On SW facing slopes, maximum radiation occurs in the afternoon, when surface soil moisture has already evaporated, so that the moisture is less available to plants than on NE facing slopes with a morning radiation maximum.

Dargie (1984, 1987) has used multivariate ordination techniques (detrended correspondence analysis: DECORANA) to analyse vegetation contrasts in Murcia, SE Spain. He concludes that temperatures are the main determinant of contrasts in floristic composition, and soil moisture of contrasts in vegetation cover and plant biomass. He also notes a significant offset of the maximum contrast from the north - south axis in a N.E -S.W. direction. Offsets vary from 7°-19°, and are attributed to the asymmetry in the daily temperature, and consequently moisture cycles. Hackett (1985) examined presence and density of indicator species in the Corbières region, S. France. He found that vegetation contrasts were associated with reduced levels of humification, and consequently of exchangeable Mg and K, on the drier south facing slopes.

These studies agree on the underlying importance of differences in solar radiation produced by aspect contrasts, but show a range of possible intermediates which influence the vegetation type, cover and biomass. The present study provides some basis for extending the discussion, by modelling some of the relevant processes explicitly. Because aspect contrasts are thought to be greatest in semi-arid mid-latitude areas, with mimimum cloud cover, the study focuses on the Almeria province of south east Spain, where annual rainfall is about 200-250mm, falling on 40-50 days. An explicit summation of direct beam solar radiation, with allowance for diffuse and long wave radiation, has been used to drive a model for soil moisture. Temperatures have not been modelled explicitly, but the observed delay of maximum temperatures after solar noon has been included to give some measure of possible offest from the north-south axis.

Vegetation and organic soil have been 'grown' in the model explicitly, but there has been no allowance for consequent changes in nutrient status. That is to say that nutrients have not been considered to be limiting for the vegetation. Vegetation types are not explicit in this type of model, but can be partially inferred from differences in seasonal persistence and biomass.

METHODOLOGY

The intensity of direct beam solar radiation is proportional to the cosine of the angle between the sun's beam and a perpendicular to the local slope surface. Intensity is greatest when the sun shines squarely on a slope facet, and falls rapidly when the sun is shining at a low angle to the surface. Allowance should also be made for attenuation of the beam as it passes through the atmosphere. This loss is least when the sun is vertically overhead and the beam therefore passes through the least thickness of atmosphere. Even with clear skies, there is some diffuse radiation from the blue sky. When the sun's beam is shaded by surrounding hills, this diffuse radiation becomes the only short-wave contribution.

The radiation received at any point is varying continuously throughout the day and throughout the year at every site. Instantaneous measurements can provide local values for the proportion of diffuse radiation and of atmospheric attenuation, but knowledge of the regular movement of the sun through the day and the seasons allows calculation of the integrated total short-wave radiation for any site, and its distribution. This analysis only provides an estimate of short-wave radiation from a cloudless sky, and radiation contrasts are greatest under these conditions. The present study has therefore concentrated on southeast Spain, an area with only 200mm rainfall a year and generally clear skies, where aspect contrasts may be expected to be high.

In areas with extensive cloud cover, radiation contrasts are low, and the dominant effect may be that due to local shading which limits the solid angle of sky which delivers diffuse radiation to a site. In a latitude transect from the north pole to the equator, aspect effects should also provide greater warming on south facing slopes, but the effect on vegetation and landforms is not consistent in direction. In high arctic latitudes, south facing slopes may thaw more frequently than north facing slopes, leading to greater solifluction. At slightly lower latitudes, north facing slopes may freeze more often, so that solifluction is greater on north facing slopes. Within the semi-arid zone, greater radiation may limit vegetation and promote soil erosion on south facing slopes, while in the humid tropics, vegetation may grow better on the slightly dryer south facing slopes. At the same time, there is a decrease in radiation contrasts towards the equator due to the increasing symmetry of solar elevation over the year. Southeast Spain is at latitude 38° N, where radiation contrasts are still strong, and the vegetation is exposed to considerable moisture stress. It is therefore an area which is expected to show strong responses to aspect differences.

Computed solar radiation levels are one important input to any model of slope evapotraspiration and hydrology. In this paper a model based on the use of Bowen ratios (Priestley and Taylor, 1972) has been used to estimate potential evapotranspiration, using average air temperatures, with a superimposed daily cycle to give the value for the ratio, and using an average albedo for the surface. This potential value has then been used to estimate actual evapotranspiration and other components of the hillslope water balance, using an explicit hillslope flow model, based on TOPMODEL (Beven and Kirkby, 1978). The details of this procedure are set out in Kirkby and Neale (1986). Actual evapotranspiration is constrained by the estimated potential value and by available soil water. Forecast net runoff of soil water is incorporated into a monthly water budget to update soil water deficit below saturation. Overland flow is obtained by integrating over the frequency distribution of daily storms which exceed the forecast deficit.

Natural vegetation growth is estimated from actual evapotranspiration and size-dependent leaf fall. Accumulation of soil organic matter is estimated from leaf fall and a temperature dependent rate of decomposition, assuming aerobic conditions. The organic matter content is used in turn to estimate the parameters of soil water storage which control subsurface flow. The biological parameters of this model have been derived from empirical data, much of it collected as part of the International Biological Programme (e.g. Lieth and Whittaker, 1975), within a global rather than a Spanish local framework. There is therefore some scope for improvement at the local scale, and no account has, at present, been taken of land use which interferes with the natural vegetation, notably grazing by sheep and goats for the area of immediate interest.

The hydrological and biological model has been run for a sufficient number of years to stabilise the biomass and runoff values, using average monthly values for rainfall. This has been found to occur in between ten and fifty years, depending mainly on the equilibrium age of the dominant vegetation. This equilibrium approach has been adopted on the reasonable premise that changes through erosion occur slowly enough to allow vegetation and organic soil to keep pace with them.

For a slope profile, overland flow may be summed downslope to give an estimate of overland flow discharge, which may in turn be used to estimate sediment discharge associated with soil erosion. In principle, flow estimates may be incorporated into a fully interactive model for slope evolution. Changes in topography due to erosion could then be used to update the radiation calculations, evapotranspiration and overland flow, to give erosion values at the next modelled time increment. At present a simpler approach has been adopted. The contrast in rates of overland flow production on opposing slopes have been used to parameterise a simpler existing slope evolution model (Kirkby, 198?) for a valley cross-section to give an estimate of the expected rate of growth of valley asymmetry. The radiation parameters have not been continuously updated, but merely checked at the end of the slope medel run to confirm that there have been no gross changes in hydrological conditions.

MODEL SPECIFICATION

The radiation model

Regional data required to estimate the direct solar beam radiation consists of latitude, overhead atmospheric attenuation and proportion of diffuse blue sky radiation. For each site, local values are needed for the slope gradient and direction, and for the elevation of the local skyline at sufficient points of the compass to estimate when the site is shaded. This data may be generated quickly for a field site, or computed for points on a slope profile, with the assumption that the valley is of indefinite extent. Similar data could also be computed for every point in a digital terrain model, and some work has been done on this although without taking account of shading effects.

The relevant equations used are as follows:

Solar declination, $d = -23.5 \cos(30m)$

Solar elevation, $\alpha = \sin^{-1}[\sin\Theta \sin d - \cos\Theta \cos d \cos(15h)]$

Solar azimuth,

$$\phi = \tan^{-1}\{[\cos d \sin(15h)]/[\sin\Theta \cos d \cos(15h) + \cos\Theta \sin d]\}$$

taking due care about the appropriate quadrant for ϕ.

where angles are taken as degrees,

h is the local time in hours and fractions of an hour (0-24)

m is the month (0 on 1st Jan to 12 on 31st Dec) and Θ is the latitude (+ in northern hemisphere).

The direct solar beam radiation at the top of the atmosphere is about 1360 W m^{-2}, with a small correction for the closer approach to the sun in winter. Ignoring diffuse radiation, the direct beam radiation on a slope surface is:

$r = r_0 \, p^{\operatorname{cosec}\alpha} [\cos\beta \sin\alpha + \sin\beta \cos\alpha \cos(\phi-\psi)]$

if α > local horizon elevation in direction ϕ.

Taking account of diffuse radiation , the total short wave radiation is:

$$R = r(1-\lambda) + p r_0 \lambda [1-\exp(-\alpha/30)]$$

without the second term if sun is below global horizon ($\alpha<0$).
where λ is the proportion of diffuse radiation,
p is the proportional attenuation for overhead sun,
β is the slope angle
and ψ is the slope azimuth (down line of local slope).

The potential evapotranspiration model

Hourly mean temperatures have been estimated from mean monthly temperatures and ranges, with the daily variation treated as a sine wave, with maximum temperatures at 3pm local solar time to allow for the delay between radiation and temperature maxima. The Bowen ratio is calculated for a given temperature, following the method of Priestley and Taylor (1972), originally calculated for an extensive area of moist pasture. Here it is approximated as:

$$B = 0.778 - 0.0396\ T + 4.714\times10^{-4}\ T^2$$

where T is the hourly mean temperature.
Potential evapotranspiration is then calculated as:

$$E_P = [(1-A)\ R - \mu\ \sigma\ (T+275)^4]/L/(1+B)]$$

where L is the latent heat of vaporisation of water,
A is the albedo of the surface,
μ is the proportion of long wave radiation escaping (*ca* 25%)
and σ is the Stefan-Boltzmann constant.

In a real situation, even with cloudless skies, the proportion of long-wave radiation lost will depend on the limits of the solid angle through which the slope views the sky. This is because the effective radiating tempeature of the atmosphere is usually lowest directly overhead, and the net outgoing long-wave radiation is greatest in this direction and decreases with increasing zenith distance. For example the net outgoing long-wave radiation from a deep basin whose rim extends 40° above the horizon will be 64-71% of that from a flat plain.

Summation of the above expression over the day provides an estimate of monthly potential evapotranspiration, for use within the slope hydrology and vegetation growth model. The details of this model are not specified here, but are taken directly from Kirkby and Neale (1986, figure 2).

The assumptions of the model used are appropriate for short vegetation rather than for forests. The nature of the vegetation cover can have a considerable effect on the importance of aspect effects. The Penman-Monteith equation (Monteith, 1965) may be presented in the form:

$$LE_A = \Omega[s/(s+\gamma)]R_N + (1-\Omega)[\rho c_P D/(\gamma r_c)$$

where $\Omega = [1+ \gamma/(s+\gamma)\ r_c/r_a)]^{-1}$

s is the slope of the local slope of the saturated humidity - temperature curve
R_N is the net radiation
r_c, r_a are the canopy and aerodynamic resistances
γ is the psychometric constant
ρ is the density and c_P the specific heat of air
D is the saturation deficit
L is the latent heat of vaporisation
and E_A is the rate of actual evapotranspiration.

Where Ω is large the surface may be considered to be isolated from conditions in the atmosphere overhead, so that the radiation effects modelled here are predominant. In contrast, small values of Ω give evapotranspiration rates which depend mainly on heat exchanges with the atmosphere. Typically extensive areas of freely transpiring short vegetation give Ω values of about 0.8, while forests give $\Omega \simeq 0.2$.

For the conditions modelled in this paper, potential evapotranspiration in the summer is so much higher than available moisture that it has little effect on the water balance of the slope. In winter, actual evapotranspiration approaches potential values, so that the model should be most reliable under these conditions. Thus the approximations which assume a high value of Ω, and high radiative control of evapotranspiration rates appear to be suitable.

The slope model

The possible erosional impact of aspect differences is illustrated for a symmetrical sinusoidal valley, which is assumed to be 200m wide, 30m deep and of indefinite length. The local horizon elevations mey then be calculated for any chosen valley orientation. The aspect contrasts in sediment yield and the long-term evolution of the slope form may then be simulated. Average rate of overland flow production from the opposite valley sides have been used to parameterise wash erosion rates in a slope model for a valley cross section. Asymmetric development is allowed by considering the valley form as repeated, so that divides and streams may migrate laterally if there is a process imbalance. This model has been written to include the slope processes of creep, splash, wash and landslides, but the rate of sliding has been set to zero to emphasise the effect of aspect, acting through the wash erosion. The model is described in full in Kirkby (1986).

Sample Results

Figure 1 shows an example of the computed local horizon for a site near the bottom of an east-west trending sine wave shaped valley (shown in figure 2a) with a southerly aspect near Almeria, at 38°N. In directions due east and west, the horizon is level, looking along the length of the valley. To north and south, the valley sides partially hide the sun at certain times of day and year. The figure shows the sun's path through the sky month by month. It may be seen that, for these rather moderate slopes, shading is mainly in the morning and evening and that, even in January, the midday sun is visible over the hilltop to the south.

Figure 2 shows the computed pattern, for each point of the same valley profile, of annual averages for radiation (fig 2b) and for simulated potential evapotranspiration (fig 2c). The only asymmetry about the north-south axis is in the delay of maximum temperature after radiation maximum, which has been set at three hours in this example. Making use of the water balance model, the equilibrium pattern of living vegetation and organic soil (d) are simulated to show a double peak at moderate gradients on the north facing slope, and a clear difference in average biomass between the two valley sides. There is a similar high contrast in the rates of overland flow production from the two sides, with average values of about 3mm and 19mm respectively from the north and south facing slopes. Only the divides are exceptional, with a forecast of high overland flow and sparse vegetation cover which merits further examination.

The effect of changing valley orientation is shown in figure 3: As might be expected, aspect contrasts are weakest when the valley slopes face east and west (line a). If the more cooler slope faces between northeast and northwest lines c,d & e), vegetation on the warmer (south facing) slope is forecast to be very insensitive to aspect. On the north facing slope however, there appears to be a critical slope gradient of about 10-20° on which vegetation is lushest, although the exact gradient varies. The largest biomass in both plants and soil is forecast to occur on slopes facing either northwest or northeast (lines b & f), whereas true north facing slopes (line d) show a less marked contrast with the south facing slopes opposite.

The long term effects of the vegetation contrast on hillslope forms have been modelled, as briefly described above. The overland flow contrast has been used to parameterise a model including splash and wash transport. This approach may underestimate the difference because it makes no allowance for the greater flow resistance offered by the thicker vegetation on the north facing slopes. On the other hand, overland flow discharge has been assumed to increase linearly with distance from the divide, whereas storms may be brief enough to limit the increase of discharge. If this is the case, wash erosion would be less effective than forecast on both slopes, and splash erosion would be proportionately more significant so that asymmetry would develop more slowly.

Figure 4 illustrates some example simulations which show the evolution of valley asymmetry from an initially symmetrical valley. At the valley bottom, the increment in stream transporting capacity is assumed to be directly proportional to height above a base level of zero. This allows a dynamic interaction between slope and channel processes. As stream behaviour is outside the scope of the present discussion, two different values of stream sediment increment have been chosen to illustrate its influence over the slope development. In figure 4a a low rate of stream activity is assumed, so that valley asymmetry develops with aggradation of the valley bottom. In figure 4b, stream activity is ten times greater, allowing overall degradation, and an even greater asymmetry. Because landslides have not been included in this model run, the maximum slopes are unrealistically steep on the north facing (right hand) slope. Inclusion of landlides reduces the extent of asymmetry and the maximum slope. At this stage, it is perhaps rash to go beyond the conclusion that aspect differences offer the potential for developing evident valley asymmetry over any period long enough for appreciable erosion. Although there are other possible causes of valley asymmetry, aspect appears to be the only one which is able to provide a consistent north-south contrast irrespective of river behaviour and lithology.

COMPARISON WITH FIELD VEGETATION DATA

Preliminary field observations have been made at several sites in Almeria province. Results show strong aspect contrasts in plant diversity, cover and biomass. At a series of sites near Turre, NW to NE facing slopes averaged 19 species per square metre, while opposing slopes supported only 5. Natural north facing slopes showed a strong increase in species diversity and biomass downslope, which was not forecast in the model, suggesting that the model has underestimated the role of lateral subsurface flow on the moister slopes. The drier south facing slopes show no comparable trend.

The most direct comparison with the model is for January biomass. Figure 5 shows simulated and measured values. The values are comparable, which provides some validation for the model, which has not been fitted to the local data at this stage. Both field and model values show an aspect contrast, although the data is not sufficiently detailed to test for small offsets in the axis of maximum asymmetry, as reported by Dargie (1987). The model appears to underestimate biomass on the north facing slopes, particularly close to north-south. Some of this discrepancy is thought to be due to underestimation of subsurface flow, but a part is also due to the assumed geometry of infinitely extending valleys, with shading effects which imperfectly reproduce the three dimensional geometry of the actual valleys. The assumed geometry is also a symmetrical one, whereas many actual slopes show at least some degree of asymmetry. This increases the shading of north facing, and hence the expected moisture and vegetation contrast.

The field data so far support one of Dargie's (1984) main conclusions, that soil moisture differences are of importance in determining vegetation cover and biomass. The model makes use of a water balance as an essential component in estimating plant growth, and so provides evidence that solar radiation differences are sufficient to drive biomass differences using a hydrological mechanism. Air temperatures are assumed the same, and soil temperatures are not explicitly forecast by the model, so that there is no basis for testing the strength of Dargie's second conclusion, that differences in floristic composition were driven mainly by temperature contrasts.

Although there remain many questions to be answered about the way in which plants adapt to moisture and temperature stress in semi-arid environments, the model is seen to provide a methodology for discussing the effects of aspect in a coherent physical framework, which can be related to climatology, hydrology and geomorphology. There is plainly scope for investigating the effects of greater subsurface flow on the moister slopes, and a need to relate vegetation growth models to the overall structure of the plant community, rather than simply to total biomass.

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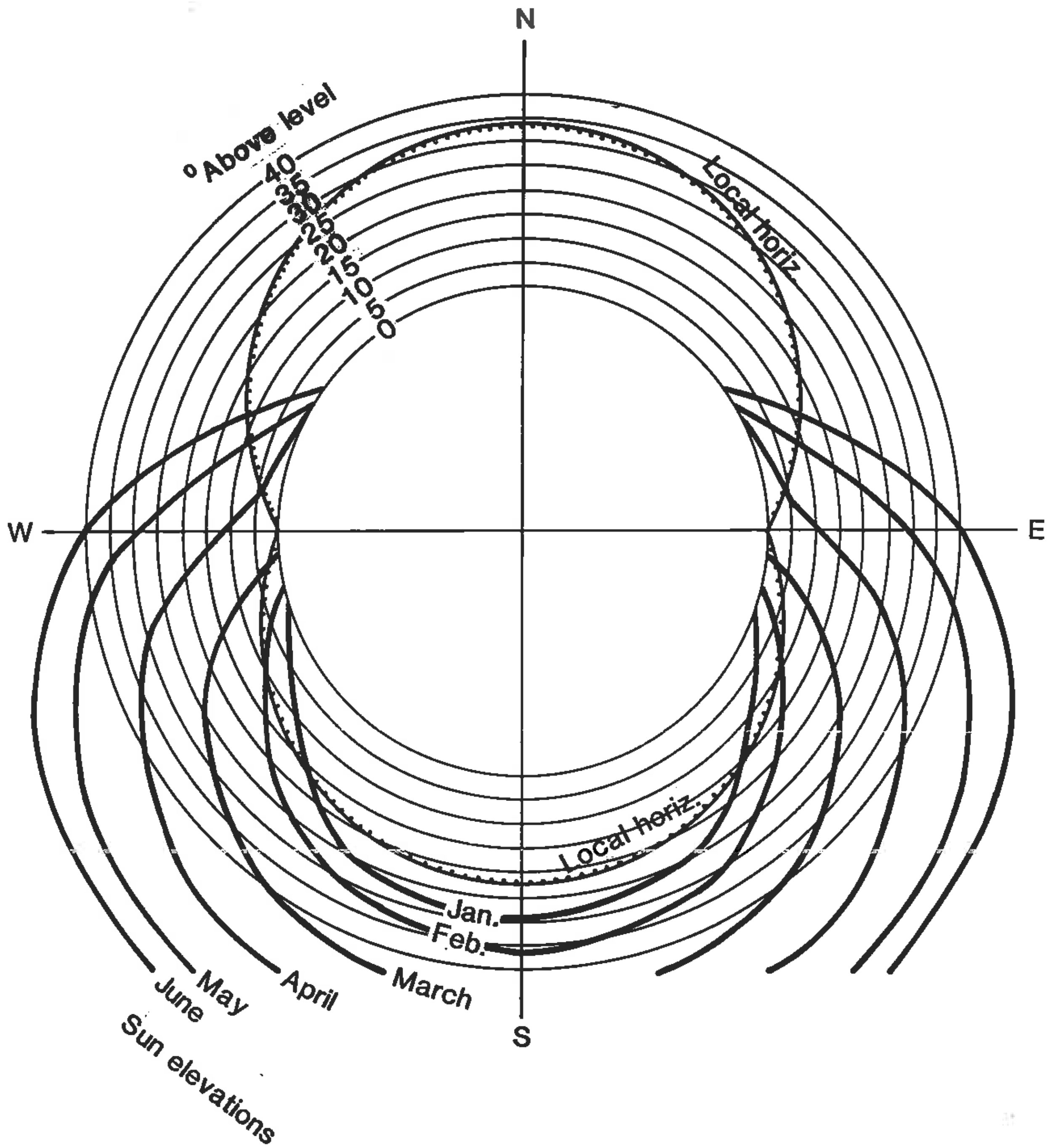
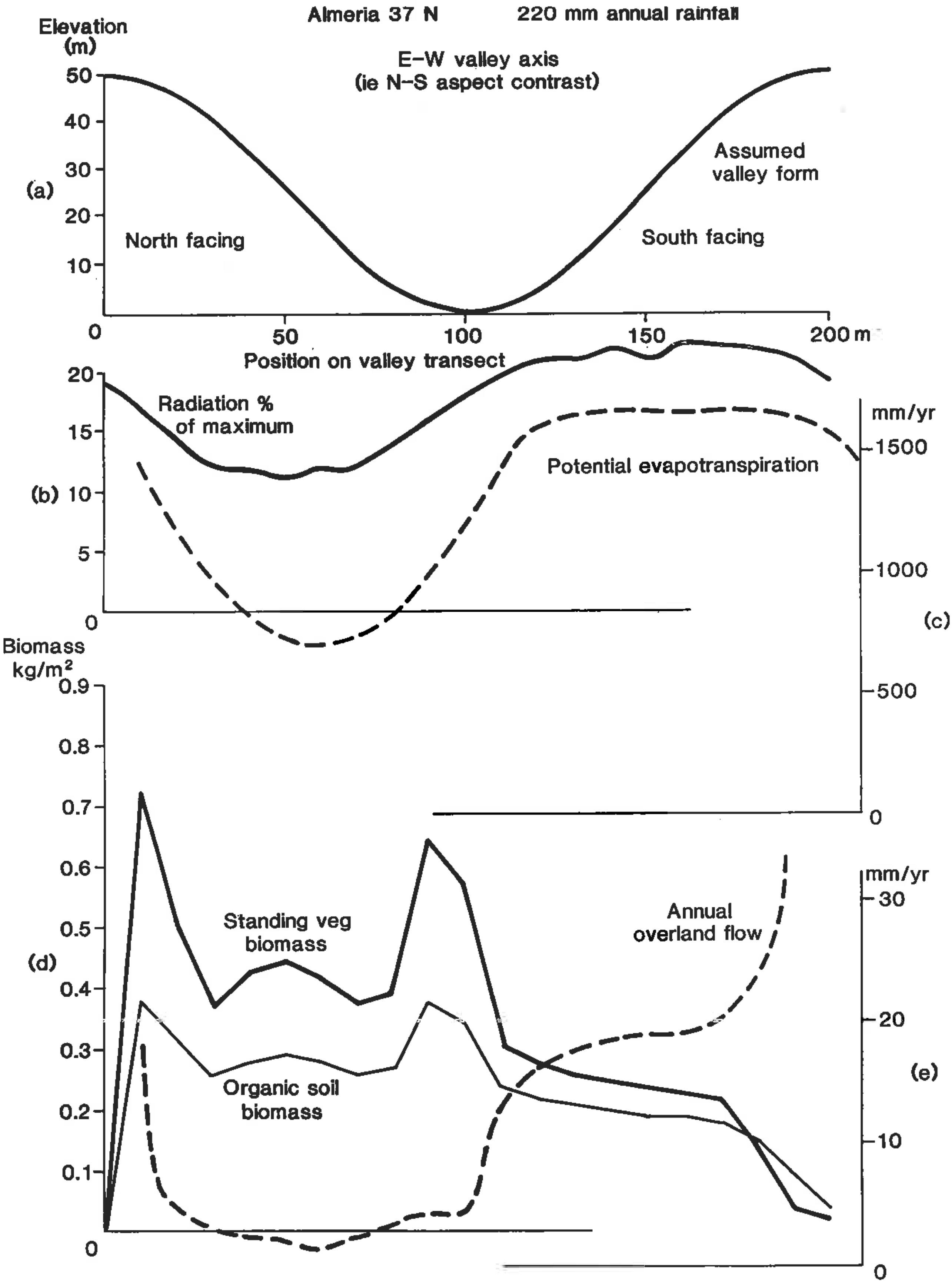


1: Computed local horizon for Point 8, near the base of the south facing slope , and solar elevation / azimuth tracks for January to June, showing the effect of local shading, particularly in the winter months.



2: Forecast variations in climatic and vegetation values on a symmetrical sinusoidal slope with directly north and south facing slopes at 37° N.

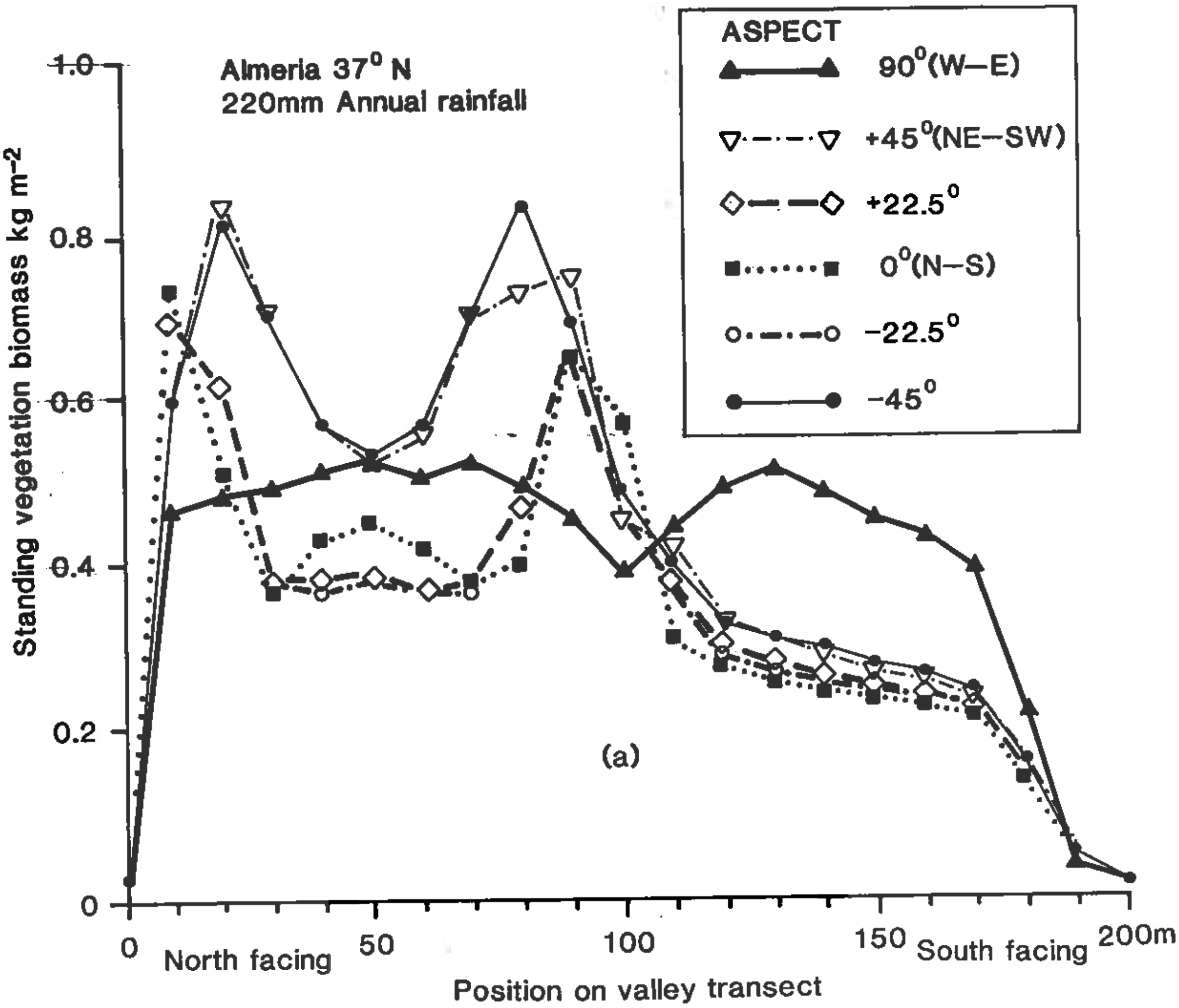
a) The assumed slope form

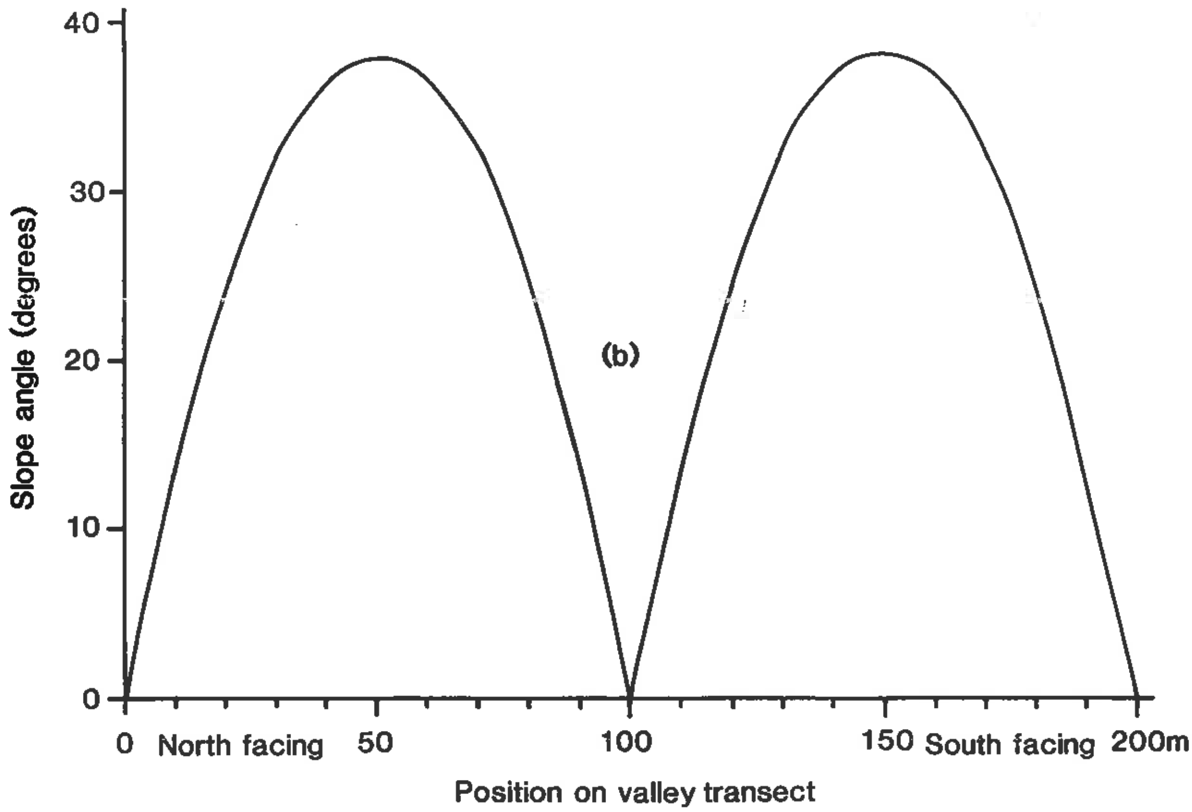
b) Percent of maximum possible radiation received over the year

c) Estimated potential annual evapotranspiration

d) Forecast Mean Standing Biomass and organic soil biomass ($kg.m^{-2}$)

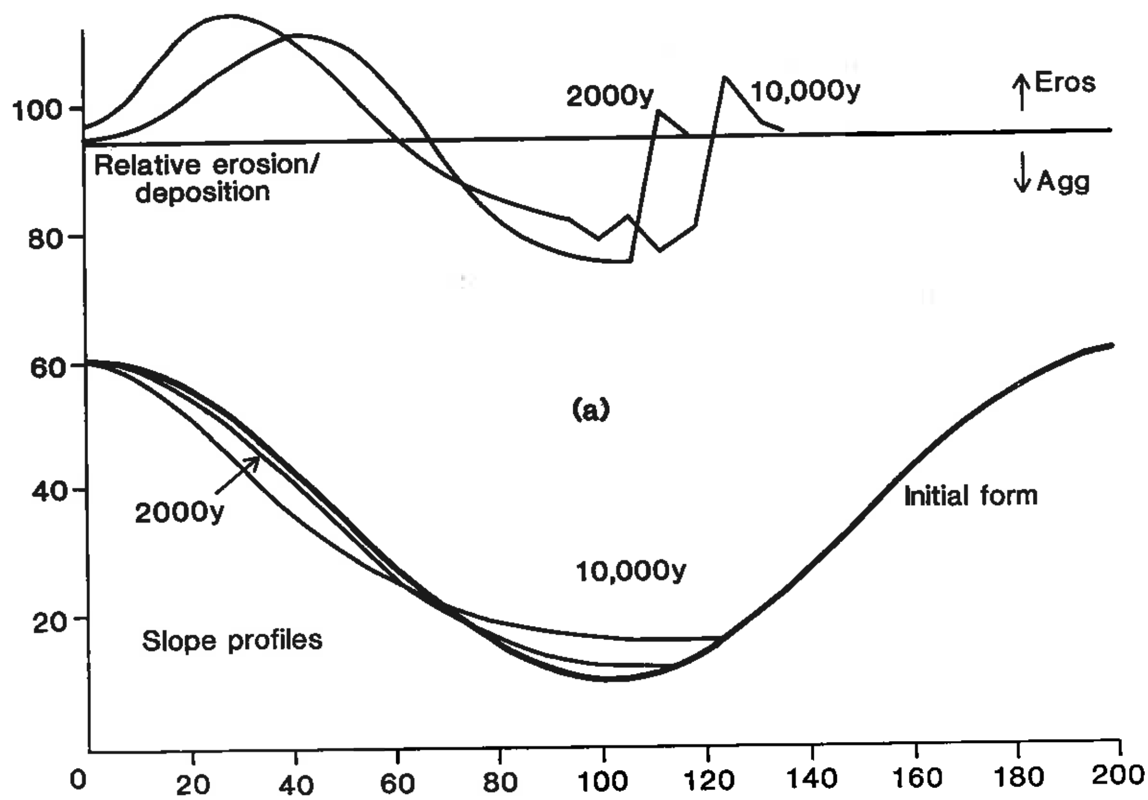
e) Forecast annual overland flow (mm)

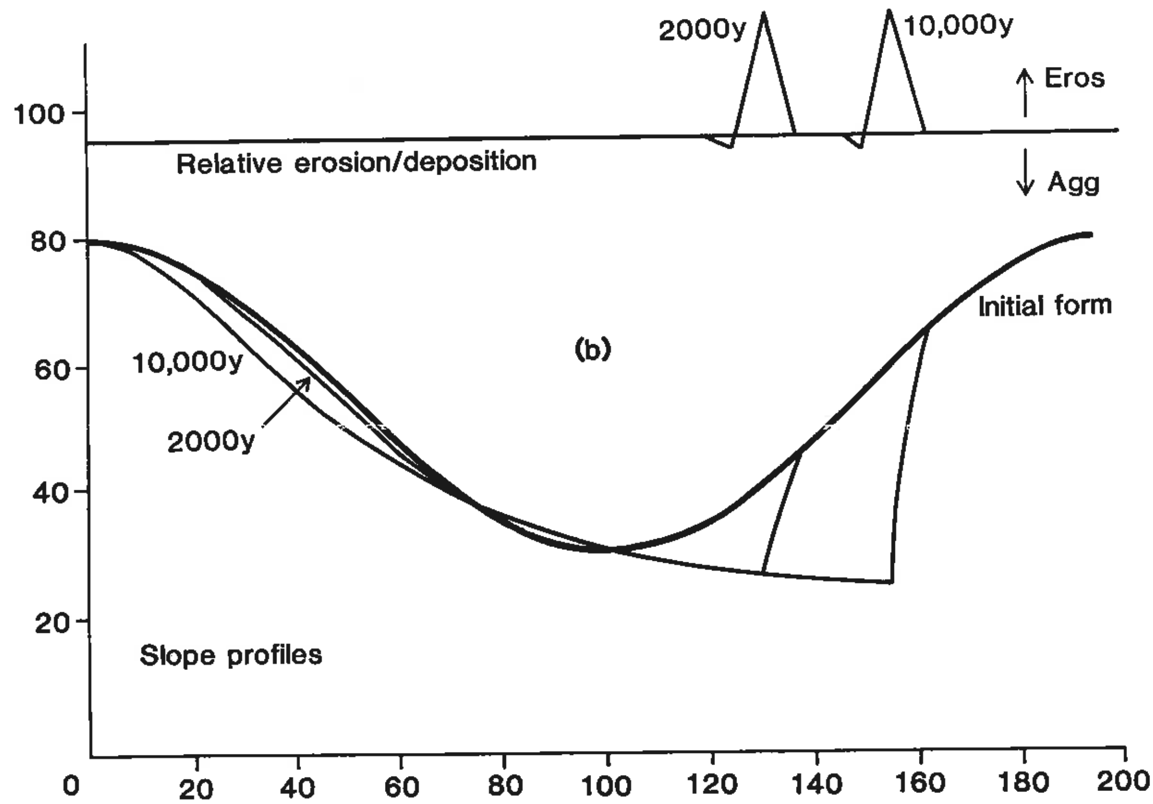




3: a) Forecast variations in mean standing biomass along the slope transect shown in figure 3, for different orientations of the valley. The aspect quoted is for the more northerly of the two opposite slopes. The 90° slope goes from West to East.

b) Slope gradient angles across the transect for comparison.

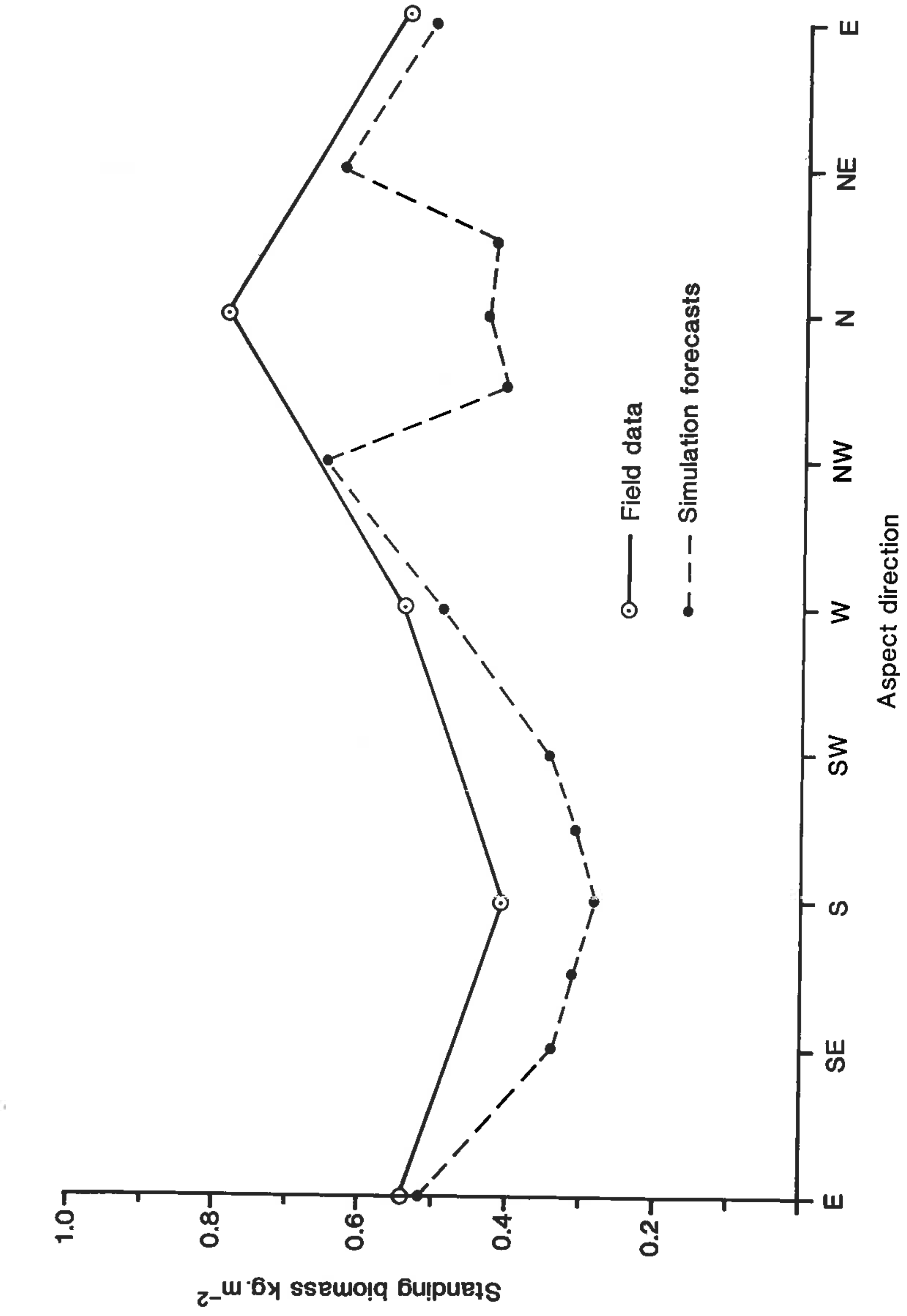




4: Forecast evolution of a north-south slope profile pair, assuming overland flow contrasts similar to those forecast above. In each case, evolution begins from the sinusoidal form assumed above. Each figure shows the relative rates of erosion and deposition (above) and the form of the slope profile (below) after 2,000 and 10,000 years.

a) Stream sediment increment $\propto 10^{-6}$ x Stream elevation

b) Stream sediment increment $\propto 10^{-5}$ x Stream elevation



5: Mid slope standing biomass ($kg.m^{-2}$) for January

a) Measured in the field near Mojacar, Almeria province.

b) Forecast from the simulation model for a symmetrical sinusoidal slope form.