9.3.2 NEUTRAL VERSUS SELECTIVE THINNING

Thinning can be conducted on randomly allocated individuals ("neutral") or can be targeted on certain species or size classes. Species-selective clearing would concentrate on those species with a high water use, low browse production and high niche overlap with grasses. This would include shallow-rooted species with a "water-spender" strategy, such as *Grewia bicolor* and exclude favoured evergreen browse species such as *Boscia albitrunca* and phreatophytes such as *Lonchocarpus capassa*.

Size-selective clearing can be used to remove a specific cohort of woody plants if they have been identified as representing bush encroachment. If the objective of clearing is primarily aesthetic, then the removal of low-growing trees and shrubs improves visibility and accessibility while creating an attractive park-like landscape. This pattern of clearing is ultimately unstable if the recruitment of young trees is suppressed.

It is possible that maximum meat production could be achieved by a mixture of browsers and grazers in a savanna which has been induced to coppice by the cutting of large trees.

There is no clear and proven functional difference between large and small woody plants as far as the suppression of grass production is concerned. The degree of competition is related to the leaf biomass, which is usually a function of the stem cross-section. Kelly, Barnes & Schwim (1978) showed that herbaceous production increased in the order woodland < large trees cleared · small trees cleared < all trees cleared, but this is probably a reflection of the leaf biomass distribution between large and small trees, which they do not give. Walker *et al* (1972) show that even a few large trees per hectare can have a major suppressive effect on grass production. Knoop (1982) indicated that the shrub *Grewia flava* interacted more strongly with grasses than did the tree *Burkea africana* It is not clear what the relative leaf biomasses were in each case. This study has shown that *Grewia bicolor* has a "grass-like" transpiration and photosynthetic strategy. Scrub-form *Colophospermum mopane*, on the other hand, does not. The interactive strength therefore seems to be related more to individual species characteristics than to growth form.

9.4 METHOD OF CLEARING

While this study did not focus on clearing methods and no data on this aspect have been presented, for the purposes of implementing the study it was necessary to review the available literature (Table 1.1) and to to lay out a small comparative trial (Scholes & Venter, in prep.). Since this study indicates that in many situations the method of bush clearing has arguably greater ecological consequences than the removal of woody plants *per se*, a brief discussion of clearing methods is appropriate.

The ideal clearing method kills woody plants but has minimal effect on other system components. Use of an inappropriate clearing method can cause erosion, loss of primary productivity, changes in the herbaceous layer species composition and increased woody plant density. Avoidance of disturbance to the soil surface and herbaceous layer is especially critical.

The least disruptive technique currently available is the broadcast application of a granular arboricide at the minimum effective dosage (for example Moore, van Niekerk & Knight 1985). Granular arboricides have a long soil life and therefore avoid the problem of synchronising application with plant growth. They are deactivated by soils with a high clay or organic matter content. The disadvantage of this method is its lack of selectivity. Selectivity can be attained by applying spot treatments at the base of selected trees, but this results in a sterile patch of soil with a diameter of about one metre which persists for many years (Scholes & Venter, in prep.). A portion of the valuable sub-canopy habitat is therefore lost. A further disadvantage of granular arboricides is the standing dead material which they leave. It can be removed by burning at a later stage, or alternatively the trees can be felled and the poison applied to the resulting coppice. Granular herbicides should not be used where there is significant vertical or lateral movement of soil water, for instance on seeplines.

Hand-felling followed by treatment of the stumps with a liquid arboricide is slightly more disruptive, especially if the debris is dragged around. The removal of the larger stems for firewood would not have a significant effect on the macro-nutrient balance of the sites investigated, and may help to redress the high cost of clearing. The branches should be left on the site to protect the herbaceous layer from herbivory until it is well established. Cut-stump treatments are most effective if applied immediately after felling during a period of active growth.

The efficacy of foliar sprays is extremely variable. The leaves of many savanna trees are protected by a thick cuticle, which retards the uptake of the arboricide. Addition of a wetting agent helps, as does application to young foliage. At the times when the plant is actively growing, however, there is also a high probability that the poison will be washed off the leaves within a day by a rainstorm. There is always a risk of wind drift when using foliar sprays, with attendant risks to other plants, animals and the operator. A carefully controlled application rate is difficult to achieve.

The use of heavy machinery for bush clearing should be avoided. Under current economic conditions it is not the cheapest option (Scholes 1986) and severe soil disruption and compaction can result (van der Weert 1974). Loamy, duplex and slightly moist soils are especially prone to compaction, which is very difficult to reverse and will lead to increased runoff and decreased primary production. Soils with a high content of smectitic clays exhibit self-mulching properties which allow them to recover from compaction. Very sandy soils are difficult to clear by bulldozer. If there is no alternative to the use of heavy machinery then a special clearing blade should be used with the minimum of traffic. Windrowing of the debris should be avoided.

Chaining and ring-barking have not been efficient methods of bush clearing in Africa.

9.5 MANAGEMENT OF INDUCED GRASSLANDS

Retention of the benefits of bush clearing and avoidance of undesirable consequences depends on conscientious post-clearing management. Bush clearing represents a deliberate and significant manipulation of the ecosystem. There can be little justification for subsequently adopting a *laissez-faire* management philosophy. Bush clearing increases the vulnerability of the system to several types of disturbance, ranging from over-grazing and erosion to nutrient depletion. In general they can be avoided by ensuring that a good grass cover is maintained after clearing. Therefore although the grazer stocking rate can be increased following clearing, it should be set conservatively to avoid over-grazing due to variability in grass production and to allow occasional burning. The congregation of of animals on the cleared areas can be minimised by ensuring that they comprise a significant portion of the total land area and by manipulating the availability of water and mineral licks.

Unless the conditions for a hydromorphic grassland are met, woody plants will regrow in the cleared area. The rate of regrowth is strongly dependent on the proportion of individuals killed during the initial clearing, since vegetative regrowth is much more rapid than regrowth from seeds. In the absence of regrowth control it is estimated that savannas in the study area will return to pre-clearing leaf biomass levels within twenty years. Rapid regrowth has a profound negative effect on the economic viability of bush clearing.

Regrowth can be suppressed by repeated clearing, mowing and the use of fire and browsers. All except the last involve significant costs, and browsing is not effective by itself. A combination of browsing and fire can be effective, but the stocking rate of grazers must be restricted to that level which allows the accumulation of about 2 $t.ha^{-1}$ of grass fuel once every three to five years (in semi-arid savannas).

Where bush encroachment is a problem the causative factors must be addressed if clearing is to have a long-lasting benefit. Conservative and flexible stocking rates, an appropriate burning regime, the encouragement of browsers and bush clearing where necessary are all essential elements of a comprehensive bush control strategy.

10.0 SUMMARY

A study was undertaken in the north-eastern lowland area of South Africa to examine the consequences of woody-plant removal on the hydrology and primary production of semi-arid savannas. Three experimental sites within a 30km were selected to represent a range of soil and vegetation conditions. Site C was on dystrophic loamy sand, dominated by *Combretum apiculatum* in the tree layer; site M on mesotrophic sandy loam with *Colophospermum mopane* and site A on eutrophic sandy clay loam with *Acacia nigrescens*. A one hectare plot at each site was completely cleared of woody plants. Key hydrological and biological variables were monitored on it and an adjacent one hectare wooded plot for three growing seasons (1982/3, 83/4 & 84/5).

The mean annual precipitation (MAP) of about 500 mm varied greatly between years and sites. Runoff increased initially after clearing but declined to below that of the control plot once a complete grass cover had been established. Runoff was greatest on the M site (10% of MAP on the basis of long-term simulations) and least on the C site (5%). Interception losses were estimated at 6-12% of MAP. Stemflow accounted for 3, 2 and 0.2 % of MAP on the M, C and A sites respectively, but could nevertheless be an important factor in the maintenance of the sub-canopy habitat.

The duration of plant-available water in the soil profile was greater on cleared than uncleared treatments in all years at all sites, but the difference decreased as grass biomass increased. Grasses were able to use water from subsoil horizons (700 mm). The increased moisture content in the subsoil in the cleared plots increased the probability of deep leaching and sodification further down the catena, especially on sandy upland sites.

Evaporation from the soil surface was 2.5 to 3.8 $mm.d^{-1}$ during the initial phase of drying. Long-term simulation indicated that evaporation ac-

counted for 30-40% of MAP, and was highest on sites with fine-textured soils. It bore a complex relationship to soil shading. It is suggested that in savannas much of the energy for evaporation is provided by advected sensible heat instead of direct radiant energy. Grass cover controls the rate of evaporation by increasing the canopy diffusive resistance.

Transpiration by trees was in the region of 10-35 and grasses 2-10 $gH_2O.gDM^{-1}.d^{-1}$. Transpiration accounted for 40-50% of MAP, being fairly equally split between trees and grass in undisturbed savanna. Various water use strategies were apparent, both between and within the tree and grass functional groups. The water use efficiency (WUE, $gDM.gH_2O^{-1}$) of trees and grass was quantitatively similar. It tended to decline in a grass as the soil dried out but increase slightly in trees.

The pre-clearing above-ground woody-plant biomass was 11.2, 21.6 and 5.7 $t.ha^{-1}$ in the C, M and A sites respectively. Of this 0.76, 0.80 and 0.66 $t.ha^{-1}$ was green leaf biomass. The woody-plant densities were 808, 984 and 524 $plants.ha^{-1}$ and the basal areas 4.5, 6.9 and 3.2 $m^2.ha^{-1}$. Herbaceous layer production varied greatly in response to rainfall on cleared and wooded treatments alike. Over the 350 to 650 $mm.y^{-1}$ range experienced during the study, herbage production on the wooded C, M and A sites was 0.6-1.5, 0.8-1.9 and 0.7-2.5 $t.ha^{-1}.y^{-1}$ respectively. On the cleared treatments it was 1.0-2.1, 1.2-2.4 and 1.3-4.5 $t.ha^{-1}.y^{-1}$. The increase was therefore a fairly consistent 0.4-0.6 on the dystrophic C and M sites, but 0.6 to 2.0 $t.ha^{-1}.y^{-1}$ on the eutrophic A site. The superior performance on the A site is mostly attributed to a shift to more efficient mesic grass species.

The grass production increase is due to enhanced performance per tuft and greater tuft density. Total forage production (including browse) decreased following clearing on the C and M sites, but increased on the A site. Total primary production probably decreased at all sites.

The study period coincided with the end of a severe drought, causing major herbaceous species composition changes in both treatments at all sites. Forbs were a major component of the herbaceous biomass at the C and M sites. Among the highly palatable grasses, *Panicum maximum* decreased following clearing at site C, but increased at M. At site A *Urochloa mosambicensis* increased greatly. No generalisations can be made about sward quality changes following clearing in this study.

A simulation model was used to relate primary production to hydrology in semi-arid savannas. It was calibrated and tested with independent data sets from the three study sites, and run with forty-year rainfall records from Skukuza. It indicated that the major hydrological consequence of reducing the woody-plant biomass was to shift the transpiration pathway from woody plants to grasses. On clayey sites evaporation from the soil surface decreases as tree biomass decreases due to the concomitant increase in grass biomass. The slightly increased interception and deep drainage losses with clearing are balanced by decreased runoff. Although the deep drainage and runoff changes are small, they are important relative to the normal magnitude of these components. The inter-annual variability of herbaceous production incr ased in absolute but not relative terms. Therefore animal stocking rates on cleared land should be conservatively set. The increase in herbaceous production was always less than the proportional decrease in woody-plant leaf biomass. This is attributed to asymmetry of competition between trees and grasses, and implies that the optimum clearing strategy is complete clearing in patches.

Grass roots occupy the entire soil profile to 1 m depth, but their peak density occurs at a shallower depth than that of tree roots. The grass water-use niche is completely included in the tree niche in the depth and time dimensions. leading to asymmetry of competition. The canonical niche overlap coefficients for water use by trees and grass are 0.74, 0.78 and 0.83 for the C, M and A sites respectively. Niche separation is almost equally due to the rooting depth and phenology axes which are nearly independent. Rooting depth is more important on coarse-textured soils and phenology is more important on fine-textured soils. The differences in transpiration rate and WUE with declining soil moisture offer another axis of separation which is not, however, independent of time.

There was evidence for competition between grass tufts in the uncleared treatments. Only at the M site was there evidence for competition between trees. The low degree of rooting depth separation is an argument against differential rooting being a major mediator of coexistence in savannas (the "Walter hypothesis"). Furthermore grasses do not appear to be clearly superior competitors for water in the topsoil: their transpiration rates and WUE, averaged over the course of a drying cycle, are similar to those of woody plants. The Walter hypothesis accounts adequately for primary production trends in savannas, but could be improved by consideration of the phenology axis and soil fertility trends. An explanation for the long-term coexistence of trees and grass in savannas must also consider competitive asymmetry and differences in longevity, water use strategy and episodic mortality due to fire, drought and browsing.

A simulation model based on published data on fire intensities indicated that fire could be used to maintain grasslands derived from semi-arid savannas in a treeless state, but only if herbivory was restricted. Once bush encroachment had occurred the viability of burning for bush control was greatly reduced, particularly if the rainfall is very variable.

Measurements of coppice regrowth by *Colophospermum mopane* indicated that basal area recovered to 50 % of the pre-clearing level in 8 years. A simple logistic growth model was used to extrapolate the regrowth trend. It predicted 80% basal area recovery in 15 years. The recovery rate is influenced by rainfall and could be retarded if the density of individuals was reduced by poisoning the stumps.

It is concluded that bush clearing need have no detrimental consequences if properly executed on selected sites. The clearing response is best on fertile, fairly heavy textured sites and worst on sandy, infertile sites. Sites of high erosion risk (such as potential sodic areas) should be avoided. The increases in secondary production may be insufficient to justify clearing on economic grounds. The level of management required to keep derived grasslands productive, treeless and uneroded is high due to their inherent instability and decreased resilience to heavy grazing. Bush clearing should only be one component of an integrated management strategy.

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A.1.1 APPENDIX 1: RAINFALL DATA

There are three data sets, one for each study site. Each line consists of an experimental day (1 = 1 July 1981), followed by the rainfall in mm.

A.1.1.1 Acacia site

1982/3		1983/4		1984/5	
135	2	470	9	845	18
143	9	481	13	853	100
146	8	493	3	866	26
152	8	494	27	873	11
162	5	495	3	882	14
178	5	496	3	883	27
185	35	497	20	887	40
200	4	500	57	899	35
207	17	501	1	908	9
227	1	502	8	921	8
243	2	505	11	923	38
246	19	506	5	925	24
247	3	517	24	926	7
262	105	521	2	930	20
286	8	524	23	932	30
297	7	526	60	934	55
		527	12	954	56
		536	11	956	42
		545	5	992	67
		547	4	995	24

556	4	1048	33
578	22		
580	57		
582	4		
583	30		
600	24		
630	19		
632	1		
633	54		

A.1.1.2 Combretum site

1982/3		1983/4		1984/5	
143	8	470	8	845	15
150	5	481	13	853	100
154	4	493	2	866	21
162	7	494	35	873	13
178	1	495	3	882	25
185	43	496	7	883	32
200	2	497	16	887	23
207	18	500	63	908	8
227	1	502	2	921	10
243	3	505	12	922	10
246	19	506	5	924	20
247	3	508	6	926	10
262	80	517	13	930	19
286	4	521	3	931	6
297	9	524	12	934	115
		526	25	954	50
		527	26	956	43
		536	12	977	14
		546	3	991	39
		547	5	995	49

551	3	1048	40
560	4		
562	4		
578	27		
580	82		
582	3		
583	27		
600	8		
630	40		
632	12		
633	75		

A.1.1.3 Mopane site

1982/3		1983/4		1984/5	
185	35	500	20	853	32
207	32	505	13	853	73
262	61	517	12	871	23
		524	9	883	75
		526	18	887	57
		527	15	899	27
		536	10	905	19
		545	12	922	20
		580	30	924	22
		582	26	934	95
		583	39	956	49
		630	48	989	36
		633	37		

A.1.2 APPENDIX 2: SAVANNA SIMULATION PROGRAMME

```
..................SAVANNA SIMULATION MODEL.......................
                         Version 2.0
                         R.J.Scholes
                   Resource Ecology Group
               University of the Witwatersrand
                        December 1984
.................................................................
program savanna(param,rain,daily,yearly,test);
type space=packed array(.1..25.) of char;
     list=array(.0..11.)of real;
     longlist=array(.0..100.)of real;
     matrix=array(.1..10,1..36.)of real;
var flagh,flagd,flago,year,month,day,rainday,
    i,j,d,t,yday,lastyear,ndepths,nhorizons:integer;
    param,rain,daily,yearly,test,overlap:text;
    diff,yover,theta,epcoef,epcon,flushrate,ep,et,eg,es,subpor,
    subn,suba,ytprod,ramax,rainin,rcmax,rcmin,dieoff,topksat,subksat,
    toppor,toptfc,toptres,subtfc,subtres,topn,topa,topm,subm,tminwet,
    gleaf,gmass,gdecay,egmax,egmin,gwue,
    gtd2,ttd2,gttd,gtime2,ttime2,gttime,
    sume,sgroott gcover,gminwet,
    tleaf,tlitter,tdecay,etmax,etmin,twue,
    tleafmax,springep,stroott,gfall,tfall,
    yrain,yrun,yint,yesoil,yetrees,yegrass,ydrain,ygprod,
    rainfall,runoffest,esoil,egrass,etrees,drain,intercepest,rainmod,
    glitter,grazing,browsing,ystore,grassint,treeint,
    glint,tlint,tlcon,glcon,
    evapmax,evapcoef,kcoef,kcon,dc,dcoef,dcon:real;
    topk,subk,tophead,subhead:longlist;
    gdeep,tdeep,thick,k,z,mm,head,mmres,mmspan,wc,
    fc,e,groott,troott,groot,troot,horizon:list;
    gniche,tniche matrix;
    sp.char;
```

```
   s1,s2:space;
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
                    PROCEDURES AND FUNCTIONS
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
.........initialises all soil information vectors..................
procedure initialise(var fc,wc,mmres,mmspan,thick:list);
var i:integer;
begin
for i:=1 to ndepths do begin
   if i=1 then thick(.i.):=z(.i.)
      else thick(.i.):=(z(.i.)-z(.i-1.));
   if horizon(.i.)=1 then begin
      fc(.i.):=thick(.i.)*toptfc;
      wc(.i.):=fc(.i.)/toppor;
      mmres(.i.):=thick(.i.)*toptres; end
   else begin
      fc(.i.):=thick(.i.)*subtfc;
      wc(.i.):=fc(.i.)/subpor;
      mmres(.i.):=thick(.i.)*subtres; end;
   mmspan(.i.):=fc(.i.)-mmres(.i.);
   thick(.i.):=thick(.i.)/10;
   end;
   i:=ndepths+1;
   wc(.i.):=1000;
   fc(.i.):=1200;
   mmres(.i.):=0;
   mmspan(.i.):=1000;
   mm(.i.):=0;
end;
```

```
........creates a lookup table of soil characteristic curve.........
procedure headarray(var headlist,klist:longlist;
                    var m,a,n,ksat:real);
var t:integer;
    lt,theta,cm:real;
begin
   headlist(.0.):=9999;
   headlist(.100.):=0;
   klist(.0.):=0;
   klist(.100.):=ksat;
   for t:=1 to 99 do begin
      theta:=t/100;
      lt:=ln(theta);
      klist(.t.):=ksat*exp(lt/2+2*ln(1-exp(m*ln(1-exp(lt/m)))));
      cm:=10.2*exp(ln((exp(lt*(-(1/m)))-1))-1*(1/n))/a;
      if cm<9999  then headlist(.t.):=cm else headlist(.t.):=9999;
   end;
end;
........unsaturated soil moisture flow..............................
procedure soilvar( var head,k,groott,troott,e,mm:list;
var sgroott,stroott,sume,drain:real);
var d,i,dt:integer;
begin
         sgroott:=0; stroott:=0; sume:=0;
         for i:=1 to ndepths do
            begin
            d:=i+1;
            theta:=(mm(.i.)-mmres(.i.))/mmspan(.i.);
            if theta<0 then theta:=0;
            if theta>1 then theta =1;
            e(.i.):=theta*100/z(.i.);
            sume:=sume+e(.i.);
            groott(.i.):=groot(.i.)*theta;
            troott(.i.):=troot(.i.)*theta;
            sgroott:=sgroott+groott(.i.);
            stroott:=stroott+troott(.i.);
            t:=trunc(100*theta);
```

```
            if horizon(.i.)=1 then head(.i.):=tophead(.t.)
               else head(.i.):=subhead(.t.);
            theta:=(mm(.d.)-mmres(.d.))/mmspan(.d.);
            if theta<0 then theta:=0;
            if theta>1 then theta:=1;
            dt:=trunc(theta*100);
            if horizon(.d.)=1 then head(.d.):=tophead(.dt.)
            else head(.d.):=subhead(.dt.);
            t:=trunc((t+dt)/2);
            if horizon(.i.)=1 then k(.i.):=topk(.t.)
            else k(.i.):=subk(.t.);
            drain:=k(.i.)*((head(.d.)-head(.i.))+thick(.i.))
                /thick(.i.);
            mm(.i.):=mm(.i.)-drain;
            if mm(.i.)<mmres(.i.) then begin
               drain:=drain-(mmres(.i.)-mm(.i.));
               mm(.i.):=mmres(.i.);
               end;
            if mm(.i.)>wc(.i.) then begin
               drain:=drain+(mm(.i.)-wc(.i.));
               mm(.i.):=wc(.i.);
               end;
            mm(.d.):=mm(.d.)+drain;
            end;  of soil layers
end;  of procedure soilvar
```

```
.........corrects finite difference errors.........................
procedure adjust(var esoil,egrass,etrees,es,eg,et:real);
var sum,part:real;
begin
   sum:=es+eg+et;
   part:=es/sum*diff;
   esoil:=esoil-part;
   es:=es-part;
   part:=eg/sum*diff;
   egrass:=egrass-part;
   eg:=eg-part;
   part:=et/sum*diff;
   etrees:=etrees-part;
   et:=et-part;
end;
........fills profile after a storm (saturated flow)................
procedure satflow(var mm:list; var rainfall:real);
var i:integer;
begin
   i:=0;
   while (i<ndepths) and (rainfall>0) do begin
      i:=i+1;
      mm(.i.):=mm(.i.)+rainfall;
      rainfall:=mm(.i.)-fc(...)
      if rainfall>0 then mm(.i.):=fc(.i.)
      else rainfall:=0;
      end;
    water in excess of field capacity fills profile upwards to satn...
   while (i>1) and (rainfall>0) do begin
      mm(.i.):=mm(.i.)+rainfall;
      rainfall:=mm(.i.)-wc(.i.);
      if rainfall>0 then mm(.i.):=wc(.i.)
      else rainfall:=0;
      i:=i-1;
      end;
end;
........interception losses.........................................
```

```
procedure interception(var rainfall,intercepest:real);
var grassint,treeint :real;
begin
      if gmass>10 then grassint:=gmass*glint/10000 else grassint:=0;
      if tleaf>10 then treeint:=tleaf*tlint/10000 else treeint:=0;
      intercepest:=grassint+treeint;
      if intercepest>rainfall then intercepest:=rainfall;
      rainfall:=rainfall-intercepest;
end;
 ............calculates runoff......................................
procedure runoff(var rainfall,runoffest:real);
var rmax,rmin,infilt:real;
begin
   if rainfall = 0 then runoffest:=0
      else begin
      rmax:=ramax*rainfall+rcmax;
      rmin:=ramin*rainfall+rcmin;
      runoffest:=rmin+gcover*(rmax-rmin);
      end;
   if runoffest>rainfall then runoffest:=rainfall;
   if runoffest<0 then runoffest:=0;
   rainfall:=rainfall-runoffest;
end;
```

```
........resets niche overlap accumulators to zero..................
procedure reset(var gniche,tniche:matrix; var gdeep,tdeep:list;
 var gtd2,ttd2,gttd,gtime2,ttime2,gttime:real);
var i,j:integer;
begin
  for i:=1 to ndepths do begin
     gdeep(.i.):=0;
     tdeep(.i.):=0;
     for j:=1 to 36 do begin
        gniche(.i,j.):=0;
        tniche(.i,j.):=0;
        end;
      end;
  gtime2:=0; ttime2:=0; ttd2:=0; gtd2:=0; gttd:=0; gttime:=0;
end;
........accumulates sums for Levins (1968) index of niche overlap....
procedure sumlevin(var g,t,gt,g2,t2:real);
const mn=0.001;
begin
   if g>mn then begin
      g2:=g2+g*g;
      if t>mn then begin t2:=t2+t*t;
         gt:=gt+g*t;
         end;
      end;
end;
........calculates overlap in two dimensions........................
procedure niche;
var i:integer;
over,gtd,td2,gd2:real;
begin
     gtd:=0; td2:=0; gd2:=0;
     write(overlap,year:5);
     for i:=1 to ndepths do
        sumlevin(gdeep(.i.),tdeep(.i.),gtd,gd2,td2);
     if gd2>0 then over:=gtd/gd2 else over:=0;
     write(overlap,over:9:5);
```

```
    if td2>0 then over:=gtd/td2 else over:=0;
    write(overlap,over:9:5);
    td2:=sqrt(td2*gd2);
    if td2>0 then over:=gtd/td2 else over:=0;
    write(overlap,over:9:5);
    if gtime2>0 then over:=gttime/gtime2 else over:=0;
    write(overlap,over:9:5);
    if ttime2>0 then over:=gttime/ttime2 else over:=0;
    write(overlap,over:9:5);
    ttime2:=sqrt(ttime2*gtime2);
    if ttime2>0 then over:=gttime/ttime2 else over:=0;
    write(overlap,over:9:5);
    if gtd2>0 then over:=gttd/gtd2 else over:=0;
    write(overlap,over:9:5);
    if ttd2>0 then over:=gttd/ttd2 else over:=0;
    write(overlap,over:9:5);
    ttd2:=sqrt(ttd2*gtd2);
    if ttd2>0 then over:=gttd/ttd2 else over:=0;
    writeln(overlap,over:9:5);
end;
```

```
          +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
INPUT/OUTPUT  PROCEDURES
          +++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
........inputs daily rainfall data..................................
          procedure inrain(var year,month,rainday,yday,day:integer;
                     var rainfall,runoffest:real);
          begin
            if flagh = 0 then begin
                ......study period data.......................................
              readln(rain,rainday,rainfall,runoffest);
              if rainday <= 0 then year:=-1;
                if rainfall<0 then year:=year+1;
                  if rainday<185 then yday:=rainday+175
                  else if rainday<550 then yday:=rainday-185
                      else if rainday<916 then yday:=rainday-556
                          else yday:=rainday-916;
              end
              ......longterm data.......................................
            else begin
              if day=32 then begin
                 readln(rain);
                 read(rain,year:4,month:4);
                 day:=1;
                 end;
               read(rain,rainfall:4);
               if rainfall = -999 then begin
                 readln(rain);
                 read(rain,year:4,month:4);
                 day:=1;
                 read(rain,rainfall:4)
                 end;
               rainday:=day+1;
               yday:=(month-1)*30+day;
               end;
          end;
           .......writes equations from the parameter file to the yearly file..
          procedure writeq(var s1,s2:space;var coef,con:real);
          begin
```

```
   writeln(yearly,' ',s1,coef:10:5,' ',s2,con:10:5,' ');
end;
procedure lineio; ..reads and writes a non-data line..................
var list: packed array(.1..75.)of char;
begin
   readln(param,sp,list);
   writeln(yearly,' ',list);
end;
procedure header; . writes header descriptions in output files.......
begin
  writeln(daily,'      |evapotranspirn      | srtt grtt|drain|',
     '    grass    |    trees    |     mm      |');
  writeln(daily,' day | pot soil tree gras|           |-age |',
     ' leaf total| leaf dead |  5  35 70 |');
  writeln(yearly,'year rain inter runoff  eg    et  ',
               '  es    mm  store excess gprod  tprod ');
end;
```

```
........inputs parameters..............................................
procedure paramin(var flagh,flagd,flago,ndepths:integer;
var toptfc,toptres,topm,topa,topksat,
subtfc,subtres,subm,suba,subksat,
evapmax,evapcoef,epcoef,epcon,ramax,rcmax,ramin,rcmin,rainmod,
springep,egmax,egmin,gwue,glint,gdecay,grazing,glitter,gminwet,
etmax,etmin,twue,tlint,tdecay,browsing,tlitter,tminwet,
tleafmax,flushrate,gfall,tfall:real;
var z,groot,troot,mm,horizon:list);
var i:integer;
begin
readln(param,sp,flagh);
readln(param,sp,flagd);
readln(param,sp,flago);
write(yearly,'  ',flagh:1,flagd:1,flago:1);
lineio;lineio;
readln(param,sp,s1,nhorizons,s2,ndepths);
writeln(yearly,' horizons',nhorizons:4,' depths ',ndepths:4);
lineio;
readln(param,sp,toptfc,toptres,topm,topa,topksat,toppor);
writeln(yearly,toptfc:8:3,toptres:9:3,topm:9:4,topa:9:4,topksat:9:5,
              toppor:7:4);
readln(param,sp,subtfc,subtres,subm,suba,subksat,subpor);
writeln(yearly,subtfc:8:3,subtres:9:3,subm:9:4,suba:9:4,subksat:9:5,
              subpor:7:4);
lineio;
for i:= 1 to ndepths do begin
   readln(param,z(.i.),groot(.i.),troot(.i.),mm(.i.),horizon(.i.));
   writeln(yearly,z(.i.):8:0,groot(.i.):8:4,
      troot(.i.):8:4,mm(.i.):8:1,horizon(.i.):4:0);
   end;
readln(param,sp,s1,evapmax,s2,evapcoef);
writeq(s1,s2,evapmax,evapcoef);
readln(param,sp,s1,epcoef,s2,epcon);writeq(s1,s2,epcoef,epcon);
readln(param,sp,s1,ramax,s2,rcmax);writeq(s1,s2,ramax,rcmax);
readln(param,sp,s1,ramin,s2,rcmin);writeq(s1,s2,ramin,rcmin);
readln(param,sp,s1,rainmod,s2,springep);
```

```
writeq(s1,s2,rainmod,springep);
lineio;
lineio;
readln(param,sp,egmax,egmin,gwue,glint,
     gdecay,grazing,gleaf,glitter,gminwet);
writeln(yearly,' ',egmax:8:4,egmin:8:4,gwue:8:5,glcon:8:4,
     gdecay:7:4,grazing:6:2,gleaf:8:1,glitter:8:1,gminwet:8:4);
readln(param,sp,etmax,etmin,twue,tlint,
     tdecay,browsing,tleaf,tlitter,tminwet);
writeln(yearly,' ',etmax:8:4,etmin:8:4,twue:8:5,tlcon:8:4,
     tdecay:7:4,grazing:6:2,tleaf:8:1,tlitter:8:1,tminwet:8:4);
readln(param,sp,s1,tleafmax,s2,flushrate);
writeq(s1,s2,tleafmax,flushrate);
readln(param,sp,s1,gfall,s2,tfall);
writeq(s1,s2,gfall,tfall);
end;    of paramin
```

```
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
                        MAIN PROGRAMME
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
begin
 ............read in parameters and starting values.................
paramin(flagh,flagd,flago,ndepths,
toptfc,toptres,topm,topa,topksat,
subtfc,subtres,subm,suba,subksat,
evapmax,evapcoef,epcoef,epcon,ramax,rcmax,ramin,rcmin,rainmod,
springep,egmax,egmin,gwue,glint,gdecay,grazing,glitter,gminwet,
etmax,etmin,twue,tlint,tdecay,browsing,tlitter,tminwet,
tleafmax,flushrate,gfall,tfall,
z,groot,troot,mm,horizon);
 ...................!nitialisation.................................
initialise(fc,wc,mmres,mmspan,thick);
topn:=1/(1+topm);                        subn:=1/(1+subm);
gmass:=gleaf+glitter;      egmin:=egmin/10000;     etmin:=etmin/10000;
gwue:=gwue*10000;  twue:=twue*10000;
headarray(tophead,topk,topm,topa,topn,topksat);
headarray(subhead,subk,subm,suba,subn,subksat);
inrain(year,month,rainday,yday,day,rainfall,runoffest);
day:=rainday;
year:=1;
if flago=1 then
  reset(gniche,tniche,gdeep,tdeep,gtd2,ttd2,gttd,
  gtime2,ttime2,gttime);
yrain:=0;  yint:=0;  yover:=0;  yrun:=0;    ygprod:=0;  ytprod:=0;
yegrass:=0;    yetrees:=0;    yesoil:=0;  mm(.11.):=0;  ystore:=0;
for i:=1 to ndepths do ystore:=ystore-mm(.i.);
if flagh = 0 then header
             else read(rain,year:4,month:4);
lastyear:=year;
 .....read rain day data and bring the date up to the raindate.......
while year>0 do begin
      inrain(year,month,rainday,yday,day,rainfall,runoffest);
   if year<>lastyear then
      begin  output annual stats and reset accumulators............
```

```
for i:=1 to ndepths do ystore:=ystore+mm(.i.);
writeln(yearly,lastyear:4,yrain:6:1,yint:6:1,yrun:6:1,
yegrass:6:1,yetrees:6:1,yesoil:6:1,mm(.11.):6:1,
ystore:7:1,yover:6:1 ygprod:8:1,ytprod:8:1);
if flago=1 then begin  ..output niche statistics if requested...
    niche;
    reset(gniche,tniche,gdeep,tdeep,
    gtd2,ttd2,gttd,gtime2,ttime2,gttime);
    end;
lastyear:=year;
yrain:=0; yint:=0; yrun:=0;ygprod:=0; ytprod:=0; yover:=0;
yegrass:=0; yetrees:=0; yesoil:=0; mm(.11.):=0; ystore:=-ystore;
end;
```

```
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
HYDROLOGY SECTION
++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
      iterate daily.......  .................................
while day<rainday do
   begin
   ep:=epcoef*cos(6.28*yday/360)+epcon;
    .........work out theta,head,k and roott for all layers....
   soilvar(head,k,groott,troott,e,mm,sgroott,stroott,sume,drain);
   egrass:=sgroott*egmax*gleaf/10000;  ...grass transpiration...
   etrees:=stroott*etmax*tleaf/10000; ...tree transpiration....
   if gmass>10 then gcover:=(4.22+15.37*ln(gmass/10))/100
            else gcover:=gmass/10*0.0422;
   esoil:=evapcoef*sume; ..............soil evaporation........
   if esoil>evapmax then esoil:=evapmax;
   if gcover>0 then if gcover<1 then esoil:=esoil*(1-gcover);
   if sgroott>0 then
    ...calculate contribution from each soil layer............
   for i:=1 to ndepths do
      begin
      eg:=groott(.i.)/sgroott*egrass;
      et:=troott(.i.)/stroott*etrees;
      es:=e(.i.)/sume*esoil;
       ...subtract evapotranspiration from each layer .........
      mm(.i.):=mm(.i.)-es-eg-et;
       ...if overestimates, adjust each proportionately........
      if mm(.i.)<mmres(.i.) then begin
          diff:=mmres(.i.)-mm(.i.);
          mm(.i.):=mmres(.i.);
          adjust(esoil,egrass,etrees,es,eg,et);
          end;
       ...accumulate niche overlap statistics if requested......
      if flago=1 then begin  j:=trunc(yday/10);
          gniche(.i,j.):=gniche(.i,j.)+eg;
          tniche(.i,j.):=tniche(.i,j.)+et;
          sumlevin(eg,et,gttd,gtd2,ttd2);
          gdeep(.i.):=gdeep(.i.)+eg;
          tdeep(.i.):-tdeep(.i.)+et;
          end;  of niche stats for one layer
```

```
   end;  of soil layers
   if flago=1 then sumlevin(egrass,etrees,gttime,
                              gtime2,ttime2);
++++++++++++++++++++++++++++++++++++++++++++ +++++++++++
             PLANT PRODUCTION SECTION
++++++++++++++++++++++++++++++++++++++++++++++++++++++++
..........grow grasses..................................
if gleaf<1 then gleaf:=0
else begin
   if egrass<0 then egrass:=0;
   eg:=egrass/gleaf;
   if eg>=egmin then begin
        gleaf:=gleaf+egrass*gwue;
        ygprod:=ygprod+egrass*gwue;
        end
   else begin
        green leaf dies if insufficient moisture present...
       dieoff.=((egmin-eg)/egmin/gfall)*gleaf;
       if dieoff>gleaf then  dieoff:=gleaf;
       if dieoff<0 then dieoff:=0;
       gleaf:=gleaf-dieoff;
       glitter:=glitter+dieoff;
       end;
    end;
......subtract decay and herbivory.......................
if glitter>1 then glitter:=glitter*gdecay;
gmass:=gleaf+glitter;
if grazing<gmass then gmass:=gmass-grazing;
............grow trees..................................
if tleaf<1 then tleaf:=0
else begin
   if etrees<0 then etrees:=0;
   et:=etrees/tleaf;
   if et>etmin then ytprod:=ytprod+etrees*twue
   else begin
        leaves fall if insufficient moisture available.......
      dieoff:=((etmin-et)/etmin/tfall)*tleaf;
```

```
      if dieoff>tleaf then dieoff:=tleaf;
      tleaf:=tleaf-dieoff;
      tlitter:=tlitter+dieoff;
      end;
    end;
  subtract decay and browsing..............................
 if tlitter>1 then tlitter:=tlitter*tdecay;
 if browsing<tleaf then tleaf:=tleaf-browsing;
  ....flush grass to 50 kg/ha if moisture present..........
 if gleaf<50 then if sgroott>gminwet then gleaf:=gleaf+50;
  ....flush trees if moisture present in summer only.......
 if tleaf<tleafmax then if ep>springep then
    if stroott>tminwet then tleaf:=tleaf+(flushrate*tleafmax);
 ...............................accumulate year statistics
yesoil:=yesoil+esoil; yegrass:=yegrass+egrass;
yetrees:=yetrees+etrees;
if flagd=1 then    ...daily output if requested.............
writeln(daily,day:5,ep:5:1 [illegible]soil:5:1,etrees:5:1,egrass:5:1,
      stroott:5:2,sgroott:[illegible]
      drain:6:2,g[illegible]6:0,g[illegible]ass:6:0,tleaf:6:0,tlitter:6:0,
      trunc((mm(.[illegible] mmres(.i.))/mmspan(.2.)*100):4,
      trunc((mm([illegible].)-mmres(.3.))/mmspan(.3.)*100):4,
      trunc((mm(.7.)-mmres(.7.))/mmspan(.7.)*100):4);
day:=day+1;
yday:=yday+1;
end;  of daily iteration while day<rainday
```

```
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
                 RAINFALL EVENT
+++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++
 if rainfall>0
    then begin
    rainfall:=rainfall*rainmod;  matches rainfall data to annual
    yrain:=yrain+rainfall;
    if gmass=0.0 then intercepest:=0 else
       interception( rainfall,intercepest);
    if flagh=1 then runoff(rainfall,runoffest)
       else rainfall:=rainfall-runoffest;
    if rainfall>0 then satflow(mm,rainfall)
       else rainfall:=0;
     ..................................... accumulate annual stats
    yover:=yover+rainfall;
    yrun:=yrun+runoffest;
    yint:=yint+intercepest;
    end;
 end,  of while year>0 do
end.
```

A.1.3 APPENDIX 3: PARAMETER FILES FOR SAVANNA

```
0     0=study data               1=40 year data
1     0=no daily output          1=daily output
0     0=no overlap statistics  1=overlap statistics
Model calibrated for 1982/3 season
*********************** MODEL PARAMETERS FOR COMBRETUM SITE ****************
--------------------Soil Parameters------------------------------------
Number of horisons      =          2 Number of soil layers =      10
    SAT        RES         M          A       KSAT    POROSITY
  0.127      0.015      0.2307     0.01921     2.10   0.7
  0.132      0.015      0.2214     0.02526     2.10   0.7
LOWER DEPTH  GROOTS  TROOTS  INITIAL  HORISON
 100         0.260   0.070     2         1
 200         0.241   0.157     2         1
 300         0.165   0.109     2         1
 400         0.114   0.123     3         2
 500         0.102   0.135     3         2
 600         0.056   0.117     3         2
 700         0.032   0.120     3         2
 800         0.010   0.063     3         2
 900         0.003   0.056     3         2
1000         0.002   0.014     3         2
Maximum daily soil evap =       2.5 Soil evaporation factor=   2.5
Evaporative potential   =     1.635 * cos(day)             +  5.087
Maximum runoff          =    0.0494 * (rainfall)           + -0.2468
Minimum runoff          =    0.0025 * (rainfall)           + -0.0125
rainfall multiplier factr     1.000 Spring Ep trigger          5.0
------------------Biological parameters------------------------------
EMAX      EMIN     WUE    CANVOL     DECAY HERBIVOR  LEAF LITTER MINWET
35         3    0.00075    5.0        0.995      0.0     50      0     0.10
 0         2    0.0010     5.0        0.995      0.0     50      0     0.15
Maximum tree leaf biomas            0 Flush rate (1/days)    =  0.07
Gleaf fall delay                   10 Tleaf fall delay       =   30
```

```
0     0=study data               1=40 year data
1     0=no daily output          1=daily output
0     0=no overlap statistics  1=overlap statistics
Model calibrated for evaporation from bare soil,for 1982/3 season
**********************MODEL PARAMETERS FOR MOPANE SITE*********************
--------------------Soil Parameters------------------------------------
Number of horisons      =          2 Number of soil layers =      10
    SAT        RES         M          A       KSAT   POSOSITY
  0.165      0.017      0.2682     0.0267      2.00   0.80
  0.165      0.027      0.2682     0.0267      2.00   0.80
LOWER DEPTH  GROOTS  TROOTS  INITIAL  HORISON
 100         0.388   0.148     2         1
 200         0.199   0.136     2         1
 300         0.118   0.126     2         1
 400         0.097   0.090     3         2
 500         0.055   0.077     3         2
 600         0.028   0.111     3         2
 700         0.028   0.104     3         2
 800         0.013   0.096     3         2
 900         0.008   0.053     3         2
1000         0.002   0.056     3         2
Maximum daily soil evap =       3.5 Soil evaporation factor=   3.5
Evaporative potential   =     1.635 * cos(day)             +  5.067
Maximum runoff          =    0.2169 * (rainfall)           + -1.5181
Minimum runoff          =    0.0477 * (rainfall)           + -0.3337
rainfall multiplier factr     1.000 Spring Ep trigger          5.0
------------------Biological parameters------------------------------
EMAX      EMIN     WUE    CANVOL     DECAY HERBIVOR  LEAF LITTER MINWET
32         3    0.0011     5.0        0.995      0.0     50      0     0.10
 7         2    0.0010     5.0        0.995      0.0     50      0     0.15
Maximum tree leaf biomas         3800 Flush rate (1/days)    =  0.07

Gleaf fall delay                   10 Tleaf fall delay       =   30
```

```
1    0=study data             1=40 year data
0    0=no daily output        1=daily output
1    0=no overlap statistics  1=overlap statistics
Model calibrated for 1983/4 seasons
********************MODEL PARAMETERS FOR ACACIA SITE********************
--------------------Soil Parameters------------------------------------
Number of horisons      =        2 Number of soil layers =     10
    SAT        RES        M          A        KSAT   POROSITY
  0.180      0.052     0.4401     0.00480     0.48  0.8
  0.185      0.052     0.4411     0.00480     0.50  0.8
LOWER DEPTH  GROOTS  TROOTS  INITIAL  HORISON
 100          0.252   0.106     2        1
 200          0.207   0.244     2        1
 300          0.124   0.160     [illegible]        1
 400          0.137   0.097     3        2
 500          0.100   0.131     3        2
 600          0.070   0.075     3        2
 7[illegible]0          0.047   0.044     3        2
 800          0.037   0.078     3        2
 900          0.017   0.065     3        2
1000          0.008   0.020     3        2
Maximum daily soil evap =       3.0 Soil evaporation factor=   3.0
Evaporative potential   =     1.635 * cos(day)           +  5.087
Maximum runoff          =    0.0771 * (rainfall)         + -0.4400
Minimum runoff          =    0.0062 * (rainfall)         + -0.0400
rainfall multiplier factr    0.090 Spring Ep trigger        5.0
------------------Biological arameters--------------------------------
EMAX     EMIN     WUE    CANVOL     DECAY HERBIVOR  LEAF LITTER MINWET
15        3    0.00220    5.0      0.995      0.0    50      0    0.10
32        2    0.0010     5.0      0.995      0.0    50      0    0.15
Maximum tree leaf biomas        [illegible]50 Flush rate (1/days)    =  0.07
Gleaf fall delay                [illegible] Tleaf fall delay        =   30
```

A.1.4 APPENDIX 4: SPECIES NAMES AND AUTHORS

Naming conventions follow Gibbs-Russell (1984).

Acacia nigrescens Oliv.
Albizia harveyi Fourn.
Boscia albitrunca (Burch.) Gilg & Ben.
Cissus cornifolia (Bak.) Planch.
Colophospermum mopane (Kirk ex Benth.) Kirk ex J. Leonard
Combretum apiculatum Sond. subsp *apiculatum*
Commiphora mollis (Oliv.) Engl.
Dalbergia melanoxylon Guill. & Perr.
Grewia bicolor Juss. This species hybridises freely with *G. monticola* Sond. and *G. subspathulata* N.E. Br.
Lannea schweinfurthii (Engl.) Engl. var *stuhlmanni* (Engl.) Kokwaro
Lonchocarpus capassa Rolfe
Ormocarpum trichocarpum (Taub.) Engl.
Sclerocarya birrea (A. Rich.) Hochst. subsp *caffra* (Sond.) Kokwaro
Terminalia prunioides Laws.
T. sericea Burch. ex DC.
Aristida congesta Roem. & Schult. subsp. *congesta*
Bothriochloa radicans (Lehm.) A. Camus
Digitaria eriantha Steud.
Eragrostis rigidior Pilg.
E. superba Peyr.
Panicum coloratum L. var. *coloratum*
P. deustum Thunb.
P. maximum Jacq.
Pogonarthria squarrosa (Roem. & Schult.) Pilg.
Schmidtia pappophoroides Steud.
Sporobolus nitens Stent
Urochloa mosambicensis (Hack.) Dandy