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Bergwind fires and the location pattern of forest patches in the southern Cape landscape, South Africa

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Abstract. A hypothesis is developed that environmental factors (rainfall and substrate) determine the potential limits of forest distribution, but that actual forest location pattern is determined by the fire pattern, which in turn is determined by the interaction between prevailing winds during dry periods and terrain physiography. The warm-temperate, mixed, evergreen forests of the study area occur in few large but isolated patches on the coastal platform and river valleys, but in many small patches in the dissected mountains. Late arrival of europeans in the area due to many deep and steep gorges through the coastal platform, and the early control over timber cutting and forest clearing prevented man from influencing the location pattern of the forests. Rainfall throughout the study area is high (900–1200 mm per annum, and expected to be higher in the mountains). The strike of geological formations cuts across forest patches. The forests persist on both deep and very shallow, rocky soils, and the soils are similar both inside and outside the forest.

The study has shown that forests on the coastal platform persisted in topographic shadow areas of the gusty, hot, desiccating northwesterly föhnlike bergwinds which are common during autumn and winter. Bergwind direction is locally changed due to barriers posed by the position and form of the mountain ridge to the windward (northern) side of the forests, and is channelled through valleys running from the mountains. Fires associated with the bergwinds would burn with higher frequency in zones in the landscape where forest is currently absent. The wind-fire pattern would furthermore cause calm conditions and a lower frequency of fire in localities where the forests have survived. A graphic model is presented to indicate the likelihood of forest persistence in topographic positions in relation to bergwind direction. The study also related understorey differences and the presence of seed of the legume tree *Virgilia divaricata* Adamson, and of charcoal in the litter layer of Witelsbos forest to such a bergwind fire which occurred an estimated 230 years ago. Forest can therefore recover from episodic, extreme fires, but disappears from areas where fires occur at high frequencies.

The results have implications for the interpretation of species-diversity patterns in the landscape in relation to disturbance and recovery, for the application of prescribed burns in catchment management, for the development of fire protection plans for commercial forestry, and for understanding the spread and control of invasive alien plants.

Key words. Biogeography, disturbance, fire, forest distribution, species diversity, wind, South Africa.

INTRODUCTION

Arguments on causes of the location pattern of indigenous forests in the southern Cape, and in southern Africa in general, revolve around the clearing of forest and the use of fire by man during the last 300 years (Phillips, 1931, 1963; King, 1938; Acocks, 1953; Granger, 1984) and limiting environmental factors, particularly edaphic factors (Van Daalen, 1981; Rutherford & Westfall, 1986; Manders, 1990). My observations suggested that, in most cases, this pattern does not conform to the edaphic changes (geology and soils) or the clearing practices and history in the southern Cape, although Phillips (1931) indicated that such factors do affect the floristic and structural composition of the forests to some extent. Charcoal was collected from the litter and feeding root zone of many seemingly mature forest stands throughout the southern Cape (Geldenhuys, 1988, 1993). Many sites in the southern Cape landscape are devoid of forest whereas similar nearby but more accessible sites carry tall, diverse and well-structured forest.

From historical records it is known that fires driven by bergwinds have devastated large areas in the southern Cape (Le Roux, 1969). Bergwinds are gusty, hot, desiccating, northwesterly to northeasterly winds which blow from the arid interior across the coastal mountains onto the coast. They are associated with low pressure cells moving from west to east along the coast (Tyson, 1964). A bergwind is similar in effect to the föhn of the European Alps, i.e. a warm dry wind descending in the lee of a mountain range (Brinkmann, 1971). Fig. 1 shows the pathways of a bergwind fire through the sclerophyllous, fire-adapted fynbos shrublands on ridges on the southern slopes of a mountain

Note: Readers of this article might also be interested in the first Book Review published on page 111 of this issue.

FIG. 1. The pathways of a bergwind fire through the sclerophyllous, fire-adapted fynbos shrublands on the ridges on the southern slopes of a mountain ridge on the Goudveld State Forest near Knysna, southern Cape, South Africa. Note that the evergreen forest in the gulleys almost remained intact.

ridge on Goudveld State Forest near Knysna in the southern Cape, South Africa. The evergreen forest remained intact. The greatest forest fire on record in the southern Cape occurred during a bergwind during February 1869 and burnt along the coastal areas from Swellendam to Uitenhage (Phillips, 1931, 1963; Edwards, 1984). Large fires at Bergplaas (1962) and Witfontein (1964), both near George, and at Longmore (1984) near Port Elizabeth burnt down large areas of pine plantations and entered the indigenous forest in several places (De Ronde, Böhmer & Droomer, 1986; Department of Environment Affairs unpublished reports; see Fig. 2 for localities). During July 1984 a fire burnt down large areas of pine stands on Kromrivier State Forest in the eastern Tsitsikamma, burnt through narrow strips of indigenous forest on the southern slopes but did not reach many other forests on the same slopes (personal observation).

In this paper a hypothesis is developed that environmental factors such as rainfall regime, geology and soils determine the potential limits of forest distribution, but that the bergwind fire pattern determines the actual location pattern of forest in the landscape. The bergwind fire hypothesis is based on the patterns of wind flow around barriers (Barry, 1981).

STUDY AREA

The southern Cape forests (Knysna Forests of Phillips, 1931 and Acocks, 1953) occur in the area between longitude 22°00′E and 24°30′E and south of the mountain ranges at approximate latitude 33°45′S. The forests occur in distinct landscape zones (Geldenhuys, 1991) with many small forests in the mountains and few but large forests confined to the coastal platform and river valleys. The forests are surrounded by fynbos, an evergreen, sclerophyllous, fire-adapted heathland and shrubland in which fine-leaved low shrubs and leafless tufted grasslike plants predominate (Rutherford & Westfall, 1986; Hilton-Taylor & Le Roux, 1989). For several reasons I selected the Tsitsikamma forests between 23°30′E and 24°15′E for this study (Fig. 2). In this area the landscape zones are well-defined and run parallel to the coast. Rainfall is high and uniform. A site study area west of Witelsbos is representative of the sites on the coastal platform (Grey *et al.*, 1987). The area was relatively unoccupied by 1870 and a controlled system of forest utilization was in operation by 1870, in contrast to the poor control over forest use and clearing in the George and Knysna area (Phillips, 1963).

The mountains form an east–west trending range with elevation between 850 m and 1300 m. Numerous ridges run south from the main range (Fig. 2). The southernmost ridges, i.e. at the junction with the coastal platform, have an east–west orientation. The geomorphology of the area is influenced by the strongly-folded sediments of the Cape Supergroup (Toerien, 1979; Grey *et al.*, 1987). This Supergroup is represented by quartzitic sandstones of the Peninsula, Goudini, Skurweberg and Baviaanskloof Formations and shales of the Cedarberg and Gydo Formations. The

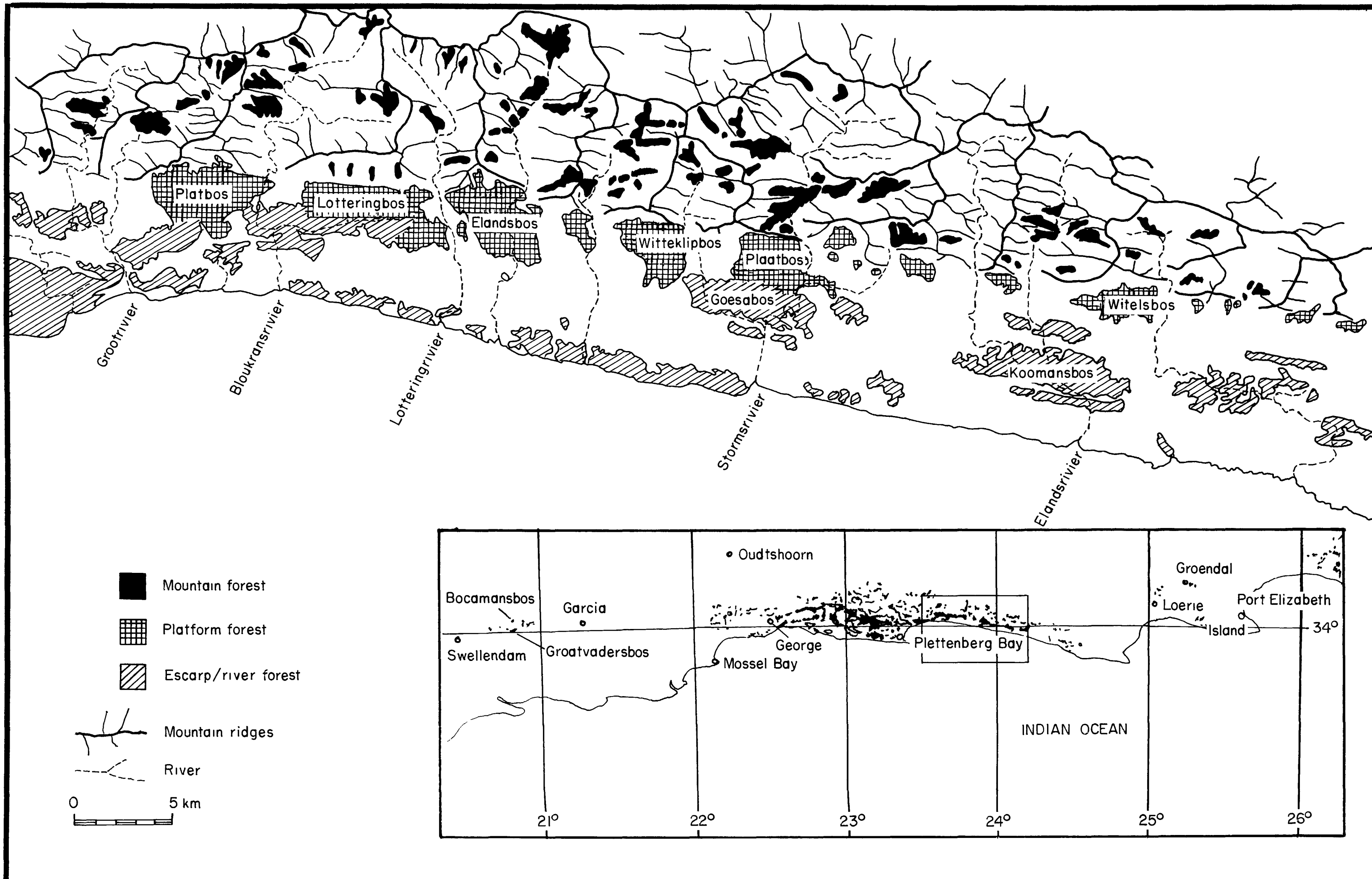

FIG. 2. The location pattern of mountain, platform, river valley and coastal scarp forests in the Tsitsikamma area of the southern Cape. The insert shows the distribution of forests to the west and east of the southern Cape (adapted from Anonymous, 1987).

formations have been folded in one anti- and one syncline in tight to nearly isoclinal folds. Their strike runs parallel to the coastline. The mountains and most of the coastal platform, both near the mountain and inland of the coastal scarp, are underlain by the resistant Peninsula Formation. The coastal platform is a Tertiary wavecut terrace with an elevation between 150 and 260 m. The Gydo shales weather easily and have been heavily dissected to form east–west orientated rivers with local relief of over 100 m in the coastal platform. Numerous rivers flow down wide valleys through the mountains, at right angles to the mountains, and have cut deep, narrow gorges through the coastal platform.

Rain falls all year with means for driest month (February) between 70 and 80 mm and high peaks of 110–120 mm during August and October (Grey *et al.*, 1987). Mean annual figures for the rainfall stations from west to east are as follows: Bloukrans 1002 mm; Lottering 1097 mm; Storms River 1221 mm; Blueliliesbush 1134 mm; and Witelsbos 1148 mm (Weather Bureau personal communication, 1985). On the platform the annual falls increase by 30 to 84 mm/km northwards (Grey *et al.*, 1987). Bergwinds frequently occur from May to August, but can start from March and continue through to September. Lightning occurs at a density of <2 flashes/km^2/year throughout the year (CSIR, 1982).

METHODS

Forest distribution at different scales was used to determine forest pattern in relation to different environmental variables. Fig. 2 was prepared from 1:50,000 topographic maps on which the forest was mapped (Geldenhuys, 1991). The topographic maps were used to describe the distribution pattern of forest patches in each of the main landscape zones.

For the platform forests the probability was calculated that forest patches occur in specific positions relative to the topography of the east–west mountain ridge on their northern boundary, and to the river gorges to their east and west. Five of the larger platform forests were selected: Platbos, Lotteringbos (northern portion), Witteklipbos, Plaatbos and Witelsbos. Elandsbos was excluded due to the western bend of the river south of the range. Five parallel lines were drawn from west to east across the forest, from river to river: the first line near the northern boundary, the fifth line near the southern boundary and the other lines at equal espacement in between. A centre line was drawn from the midpoint of the first line to the midpoint of the fifth line. On each line the distance was measured from river to river, and from the centre line to the western and eastern forest boundary. The Chi-square test for goodness of fit (STSC, 1986) was used to calculate various probabilities about the location pattern of the platform forests.

Results from the site study area west of Witelsbos were used to determine the site conditions to the east and west of the Elands River and south of the mountains, both inside and outside the forest.

In Witelsbos, on level terrain near the southern boundary of the forest, the understorey showed and abrupt change in height, density and composition, from north to south. This line of abrupt change was mapped. Several soil pits were dug and the forest composition was sampled on either side of the change (Geldenhuys, in prep.)

RESULTS

Location pattern of forest in landscape zones

The largest forests occur on the coastal platform immediately south of the southernmost mountain ridge and along the east–west trending river valleys in the coastal platform (Fig. 2). The platform forests occur west of each north–south river gorge cutting through the platform. Their northern boundary occurs on the steep footslope of the southernmost ridge, near its eastern end. Forest is absent from the platform to the east of each gorge. Those sites carry only fynbos, or *Pinus* plantations planted into fynbos. Forests in the river valleys occur up to the sharp edges between the coastal platform and the valley, on both the northern and southern sides of the valleys. On ridges running from the coastal platform into the valley, forest occurs at a level much lower than the upper edge of the valley. Forests along the coastal scarp occur in positions very similar to those in river valleys.

The smallest forest patches occur in the mountains in several types of situations. Most mountain forests occur west of the streams, near the bottoms of the valleys, whereas forests are absent east of those same streams, for example the forests north of Plaatbos. A few mountain forests occur immediately below precipitous krantzes on concave slopes. No forests occur near the tops of the ridges except where the slope to the north is more gentle than the slope to the south of the ridge and the southern slope is straight or concave to near the top of the ridge. Near the lower end of some ridges, forest occurs in the valley of a first-order stream within the forking end of the ridge.

Location pattern of forest on coastal platform near the mountain

The mean forested area of the five studied platform forests (Table 1) is 58.8% and the areas for individual forests (43.5 to 67.3%) do not differ significantly (Chi-square = 7.27, 4 df, $P = 0.122$) from this mean value. However, the Witelsbos forest has made a large contribution to the Chi-square value (4.072) which suggests that its size is significantly smaller than the expected mean.

Several site features would suggest that the platform forests should have a symmetric distribution on either side of the centre north–south line between the two gorges: the gentle slope at the foot south of the southernmost ridge; the uniform topography between the two adjacent north–south river gorges; and the parallel east–west strike of the geological formations. However, it is clear from Table 1 that the eastern half of the area between two rivers is 84.8% forested whereas the western half is only 31.3% forested. Fig. 2 also shows that the shape and size of the open area west of each forest varies. Along several lines in Witteklipbos and Witelsbos the western boundary is situated to the

TABLE 1. The location pattern of five Tsitsikamma platform forests. A negative value indicates that the forest occurs to the east of the center line at that point.

Forest	Line*	Distance: river to river (km)	Forest area as % of distance from centre line to river: To west	To east	Comments on orientation and form of mountain ridge to the north of the forest
Platbos	1	7.4	50.0	98.6	[1]Arch concave
	2	7.3	49.7	97.9	[2]WSW to ENE
	3	7.1	46.5	90.1	[3]Precipitous from narrow
	4	7.3	35.9	84.1	ridge to river
	5	7.2	26.4	90.3	
Lotteringbos	1	8.8	53.4	88.6	[1]Straight W to E
	2	8.9	53.1	83.6	[2]W to E
	3	9.1	53.8	75.8	[3]Steep slope of rounded
	4	9.2	53.6	75.4	ridge; platform next
	5	9.1	54.1	81.8	to river
Witteklipbos	1	4.8	46.3	82.1	[1]Straight WNW to ESE
	2	4.7	47.3	86.0	[2]W to E
	3	4.7	31.9	87.2	[3]Narrow steep ridge
	4	5.3	5.7	71.7	down to river
	5	5.4	− 1.9	68.5	
Plaatbos	1	5.9	15.3	84.7	[1]Arch concave
	2	5.5	14.5	90.9	[2]WSW to ENE
	3	5.4	24.3	99.1	[3]Narrow ridge with
	4	5.2	40.4	100.0	valley north of ridge
	5	4.9	36.7	98.0	
Witelsbos	1	7.0	− 2.9	82.9	[1]Arch convex
	2	7.0	− 4.3	81.4	[2]WNW to ESE
	3	7.0	33.1	82.0	[3]Platform next to river.
	4	7.0	10.1	82.0	Ridge east of river more south
	5	7.0	− 10.1	80.6	than ridge west of river

* Parallel East-west lines measured from river to river. Line 1 is nearest to mountain and line 5 the furthest away.
[1] Orientation of ridge from river to river in relation to forest to the south.
[2] Orientation of western end of ridge.
[3] Shape of eastern end of ridge and type of connection between ridge and river.

east of the centre line. The hypothesis was tested that, for each forest, the open area to the west of the forest was the same along each of the measured lines. The Chi-square value was non-significant for Platbos (except for a large value for line five), Lotteringbos and Plaatbos (except for large values of lines four and five) but significant for Witteklipbos ($P = 0.000016$) and Witelsbos ($P = 0.0011$). For the eastern portion the hypothesis was tested that the distance from the centre line to the eastern margin, expressed as a percentage of the distance to the eastern river, was the same for the five lines of each forest. For all the forests the deviations from the mean were non-significant. Note the relation between the shape of the forest and the orientation of the ridge to its north, particularly the western end, the position of this ridge in relation to the southernmost ridge west of the gorge, the shape of the eastern end of the ridge and its connection with the river, and the presence or absence of an east–west river valley to the south of the forest (Table 1; Fig. 2).

Edaphic conditions inside and outside forest

The Tsitsikamma site study area covers the coastal platform on either side of the Elands river (Fig. 3). The area shows the typical forest distribution pattern as observed in the rest of the Tsitsikamma (Fig. 2). The area has been stratified into mountain footslopes, central plateau next to the mountain, and the coastal plateau. A site survey in the study area produced results which are relevant to this study (Grey *et al.*, 1987).

Effective rooting depth for *Pinus* species ranged between 250 and 1 200 mm (see also Payn & Clough, 1988). The shallower soils are in the northern part of the area and are associated with mountainous terrain. The northern parts of both Puntjiesbos and Witelsbos grow on such soils. Soil depth of the central plateau was between 600 and 800 mm whereas similarly deep soils occur in places on the coastal plateau south of Koomansbos.

Site units on the coastal platform showed close agreement with topography, and tend to follow the minor drainage lines and are aligned mainly in a north–south direction. They clearly do not follow the forest-fynbos (plantation) boundaries. Between Puntjiesbos and Witelsbos on the central plateau and south of Koomansbos on the coastal plateau the soils are deep, hydromorphic and podzolic, both inside and outside the forests. The central plateau soils

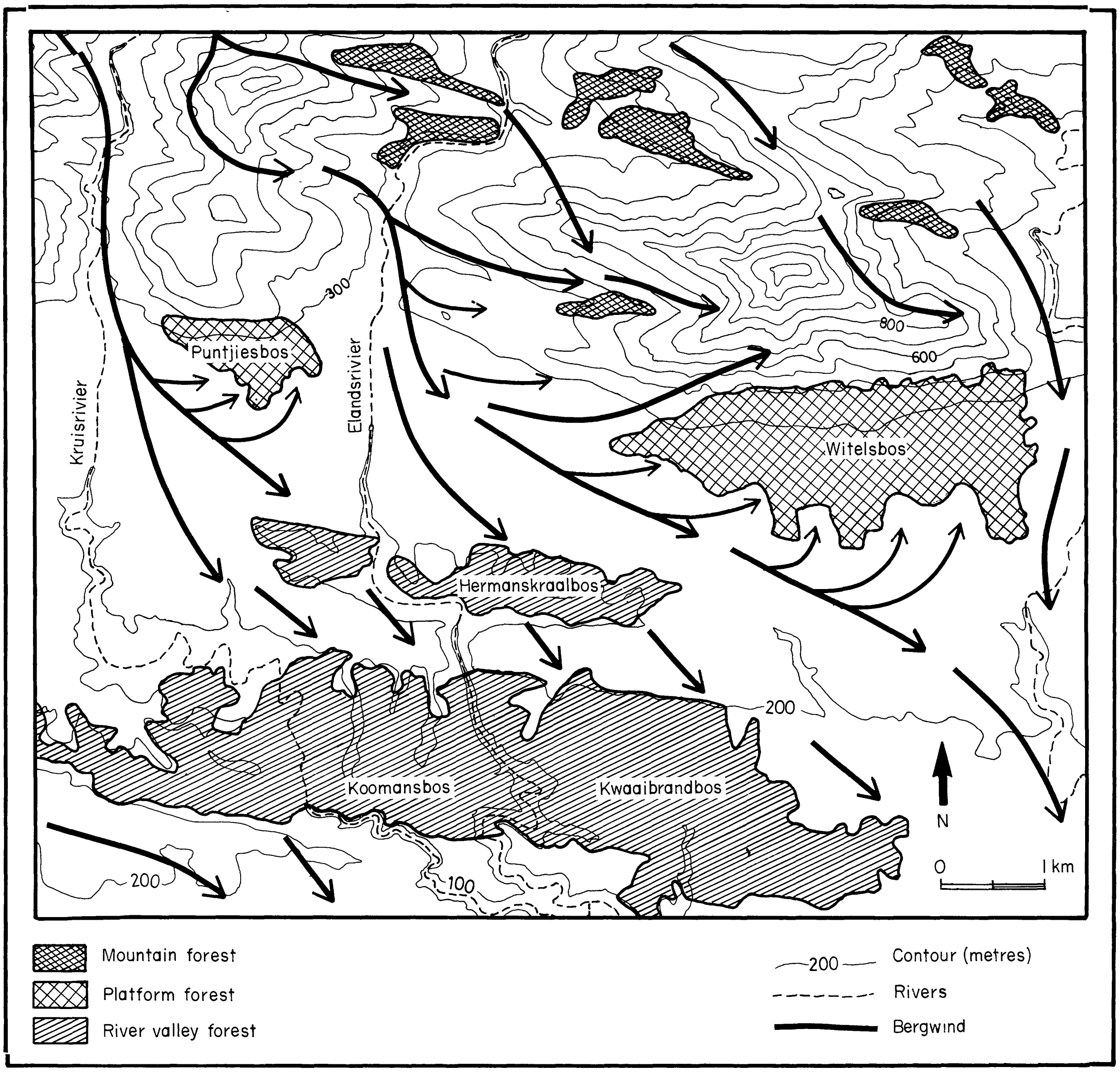

FIG. 3. Part of the Tsitsikamma site study area. Note the hypothesized flow patterns of a bergwind in relation to the location pattern of mountain, platform and river valley forest.

overlie sandstone whereas the soils of the coastal plateau overlie deep clays. Soils of the incisions into shales of the Koomansbos area are richer in nutrients and have good water holding capacity.

The *Pinus* stands were established on areas which were covered by fynbos. Various forest species are scattered to common underneath the mature pine stands, both on the central and coastal plateaux (also personal observation).

Earthworm and arthropod dominated mull-humus are sometimes found under the indigenous forest, particularly on shales, but the dominant humus form in the forest is a microbiotic mull. Humus layers on the plateau soils outside forest are highly disturbed due to burning, grazing, cultivation and planting of *Pinus* plantations.

Understorey differences in Witelsbos forest

The study area in Witelsbos is shown in Fig. 4. Note the pointed-finger pattern towards the southwest of the southern boundary of many of the platform forests which are not bounded by an east–west river valley (Fig. 2). This form of southern boundary is particularly well-developed in Witelsbos. Inside the forest the abrupt change in the density and composition of the understorey follows a similar pattern up to 300 m from the present road. Comparison of various variables from five paired samples taken on either side of the change, showed the following (Geldenhuys, in prep.).

The soil profiles were basically similar (Lamotte soil

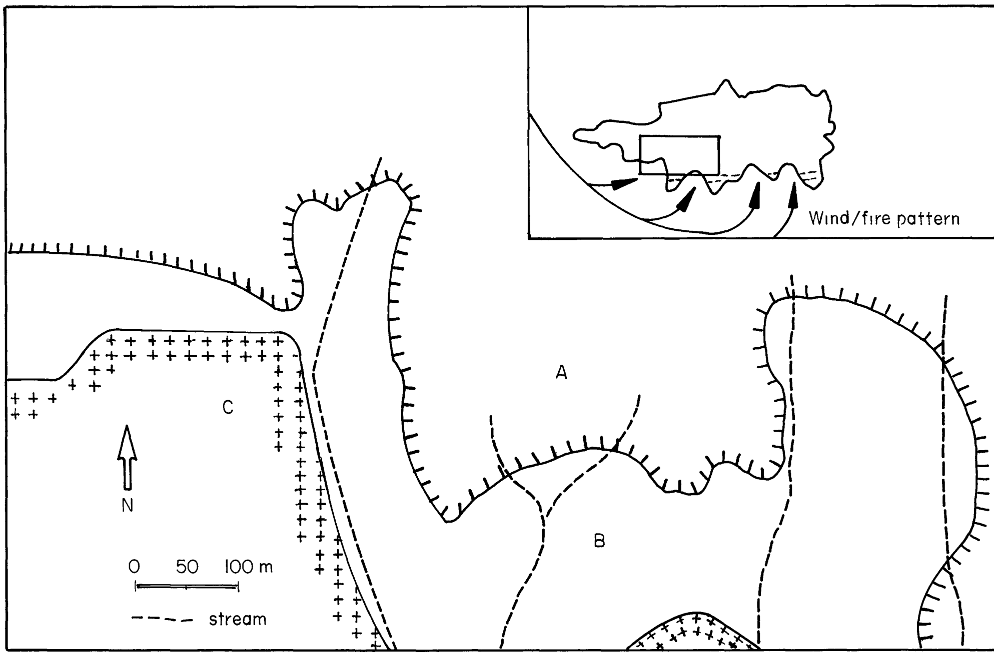

FIG. 4. The Witelsbos study area. Areas A and B are indigenous forest of about 20 m height. Area C is a pine stand established into fynbos shrubland on the forest margin. The understorey of area A is a tall, dense stand of the shrub *Trichocladus crinitus* (Thunb.) Pers., and of area B is a sparse stand of seedlings and saplings of canopy tree species. Abundant charcoal and seeds of the legume pioneer tree *Virgilia divaricata* Adamson are present in the feeding root zone of area B.

form or gleyic podzols) and do not explain the abrupt understorey change. The topography of the site is very level (1–3% slope). Drainage is moderate with temporary waterlogging. Effective rooting depth is 500–800 mm.

North of the change, in the old growth forest (area A), the understorey consists of a dense, tall (3–5 m) stand of the shrub *Trichocladus crinitus* (Thunb.) Pers., which is typical of the platform forests (Geldenhuys, 1993). The mean density of stems of *T. crinitus* of 1–5 cm DBH is 14,159 stems/ha (CV = 44.4%), in addition to the 1340 (CV = 31.1%) stems/ha of tree regeneration of the same size. South of the change, i.e. regrowth forest (area B), only scattered clumps of *T. crinitus* occur (none recorded in the 1–5 cm DBH category), with 2496 stems/ha (CV = 39.9%) of tree regeneration of the 1–5 cm DBH category. A few to abundant stems of $<$ 1 cm DBH of the forest ecotone shrub *Myrsine africana* occur in this area.

Composition of the canopy and regeneration, and the diameter distribution, of the two areas, is summarized in Table 2, and does not differ much between the two sites. Canopy height of the mixed stands on either side of the change is variable, 18–23 m. Mean DBH of trees $\geq$ 5 cm DBH is 18.8 cm in old growth forest and 16.2 cm in the regrowth forest, and for trees $\geq$ 20 cm DBH, it is 34.5 cm and 33.2 cm respectively. Basal area of trees $\geq$ 20 cm DBH (cross-sectional area of all stems at breast height) is 43.67 m^2 for the old growth forest and 32.43 m^2 for the regrowth forest.

In the regrowth forest charcoal (one to seventy five pieces per 0.135 m^2) and seeds (318 seeds/m^2; CV = 61.6%) of the pioneer legume tree *Virgilia divaricata* Adamson are present in all the soil samples taken from the upper 5 cm of the soil, i.e. in the feeding root zone below the litter. In the old growth forest two to four pieces of charcoal in three sites, and legume seeds (15–685/m^2 [CV = 191.5%] from four sites) were found. Some *V. divaricta* seed germinated on the sides of the soil pits.

Stem sections of *Podocarpus falcatus* were collected during forest clearing for building of the road south of the study area. Ring counts showed that the oldest tree was 215 years, allowing for a 5% underestimate in the dendrochronological age determination (McNaughton & Tyson, 1979). The age of the other large trees ranged between 108 and 126 years.

DISCUSSION

Forest location pattern in relation to clearing and site conditions

The location pattern of forest in the study area is not related to historic clearing of forest. Because many deep gorges cut through the coastal platform, the area was very inaccessible before the modern network of roads was built. The first permanent residents settled in the Witelsbos area between 1850 and 1860 (Grey *et al.*, 1987) at a time when relatively good control was enforced on the woodcutter settlers, and most of the area remained relatively unoccupied (Phillips, 1963). Plantations of *Pinus* and *Eucalyptus* species were established outside the forest in fynbos (Department of Forestry unpublished reports).

The pattern is also not related to rainfall, geology, or

TABLE 2. Floristic and structural composition of old growth and regrowth forest in Witelsbos. (a) Species composition: importance values (IV), based on relative frequency (Freq%), relative density (Den%) and relative basal area (Bas%) for trees ≥ 5 cm DBH, and relative frequency and relative density for regeneration (stems 1–4.9 cm DBH), for species in the Witelsbos old growth forest and regrowth forest respectively. (b) Diameter class distribution.

(a) Species composition

	Old growth forest Trees ≥ 5 cm DBH				Trees < 5 cm DBH			Regrowth forest Trees ≥ 5 cm DBH				Trees < 5 cm DBH		
Species	Freq%	Den%	Bas%	IV	Freq%	Den%	IV	Freq%	Den%	Bas%	IV	Freq%	Den%	IV
Podocarpus falcatus (Thunb.) R. Br. ex Mirb.	20	2.8	5.61	9.5	20	0.4	10.2	80	2.4	1.89	28.1	0	0.0	0.0
Podocarpus latifolius (Thunb.) R. Br. ex Mirb.	100	21.8	12.74	44.8	100	17.2	58.6	100	15.3	15.90	43.7	40	0.6	20.3
Ocotea bullata (Burch.) Baill.	60	5.6	4.03	23.2	100	31.7	65.9	100	10.0	26.78	45.6	100	19.0	59.5
Platylophus trifoliatus (L.f.) D. Don	40	4.2	17.46	20.5	—	—	—	60	3.2	5.24	22.8	—	—	—
Pterocelastrus tricuspidatus (Lam.) Sond.	100	10.2	20.43	43.5	20	0.4	10.2	100	23.7	25.11	49.6	80	5.4	42.7
Cassine eucleiformis (Eckl. & Zeyh.) Kuntze	40	1.4	0.75	14.0	—	—	—	100	2.8	1.37	34.7	20	0.2	10.1
Cassine papillosa (Hochst.) Kuntze	60	2.8	0.52	22.1	80	3.0	41.5	—	—	—	—	100	2.4	51.2
Apodytes dimidiata E. Mey. ex Arn.	80	5.6	4.05	29.9	20	1.1	10.6	40	0.8	0.11	13.6	60	0.6	30.3
Curtisia dentata (Burm.f.) C.A. Sm.	80	5.6	3.90	29.8	20	0.7	10.4	60	3.2	3.76	22.3	40	0.4	20.2
Rapanea melanophloeos (L.) Mez	40	1.9	1.64	14.5	60	6.0	33.0	80	1.6	0.31	27.3	80	5.0	42.5
Olea capensis L. subsp macrocarpa (C.H.Wr.) Verdoorn	100	4.2	11.51	38.6	80	6.0	43.0	60	1.2	1.46	20.9	100	7.2	53.6
Olea capensis L. capensis	60	2.3	2.25	21.5	20	2.2	11.1	40	2.4	0.48	14.3	40	6.2	23.1
Nuxia floribunda Benth.	60	1.4	1.00	20.8	40	0.7	20.4	20	0.8	0.50	7.1	—	—	—
Gonioma kamassi E. Mey.	100	17.6	6.02	41.2	100	15.7	57.8	100	20.5	5.41	42.0	100	39.5	69.7
Burchellia bubalina (L.f.) Sims	80	2.8	0.37	27.7	40	1.5	20.7	—	—	—	—	—	—	—
Psydrax obovata (Eckl. & Zeyh.) Bridson	60	2.3	4.12	22.1	40	1.5	20.7	—	—	—	—	20	0.2	10.1
Brachylaena glabra (L.f.) Druce	40	2.3	1.32	14.5	80	3.7	41.9	60	7.2	2.88	23.4	100	11.4	55.7

(b) Diameter class distribution

DBH class	Number of stems per hectare	
cm	Old growth forest	Regrowth forest
5– 9.9	65	110
10–19.9	535	640
20–29.9	215	265
30–39.9	145	120
40–49.9	55	55
50–59.9	35	35
60 +	30	20

soils. Annual rainfall throughout the coastal platform is high (900–1200 mm) and can be expected to be higher in the mountains. In parts of the Tsitsikamma and the larger southern Cape, forest persists in areas with rainfall down to 500 mm (Geldenhuys, 1991). The strike of geological formations cuts across forest patches. Forest grows on both deep and very shallow soils, whereas the soils are similar both inside and outside the forest. The steep slopes of the incised valleys and coastal scarp support large areas of forest. The coastal scarp soils are very rocky and shallow, and the forests are exposed to the saline winds from the ocean.

Forests persist in bergwind shadow areas

Historical records of the larger, devastating fires (Phillips, 1963; Le Roux, 1969; Edwards, 1984; De Ronde *et al.*, 1986; Department of Forestry unpublished reports), the fire danger rating system and the procedures of fire prevention systems all suggest that fires are most likely to occur and persist during the hot, desiccating bergwind periods. Fires during bergwinds would most likely follow the flow direction of the wind and would destroy forests along that route. I suggest that forests persisted in bergwind shadow areas where fires are less likely to occur at frequent intervals (Fig. 3).

Wind flow patterns across barriers

Flow patterns of air across barriers (Barry, 1981) explain most of the location patterns of forests in the study area. The mountains change the flow of northwesterly bergwinds and channel them with greater velocity southwards through the valleys. Their severity is particulary felt in the neighbourhood of a pass or break in a mountain chain, as at George (McNaughton in Sim, 1907; personal observation). South of the mountains they continue in a southeasterly direction across the coastal platform. This explains the absence of forest on the central plateau east of each gorge, but the presence of large forests west of the gorges, and the absence of forest on the coastal plateau (Fig. 2; Table 1).

The orientation, position, and shape of the crest of the ridges on the western and eastern extremes of the southernmost ridges have a marked effect on the shapes of the open areas to the west and east of the platform forests.

When the western tip of the ridge points to the northwest, or if the ridge tip east of the gorge is situated further north than the ridge tip west of the gorge, the fynbos area between the forest and the western river gorge is large because of the direct flow of the wind onto the platform as at Witelsbos.

When the western tip of the ridge points towards the southwest, the fynbos area between the forest and the western gorge is small as at Platbos, Lotteringbos, Elandsbos and Witteklipbos.

When the ridge east of the gorge is situated further south than the ridge west of the gorge, fires burn in a southwesterly direction onto the platform west of the gorge, for a short distance, as at Lotteringbos and Elandsbos.

The orientation of the gorge through the platform has no influence on the location pattern of the platform forest such as the eastern boundary of Elandsbos and Witteklipbos. The gorges are narrow and fires can easily jump a gorge as at Witteklipbos and along the coastal plateau.

On the platform, wind of lesser velocity will branch away from the main southeasterly air flow, to blow in a northeasterly direction. The velocity of the branching wind will depend on the velocity of the main air flow and the velocity gradient between this flow and the wind shadow area in the northeastern corner of the platform. This explains the pointed-finger pattern towards the southwest along the southern boundary of some forests, such as Witteklipbos and Witelsbos (Figs 2 and 3). Occasional fires under extreme bergwinds would destroy the forest beyond the margin of the more regular fires such as in Witelsbos (Fig. 4). The southern boundaries of some platform forests would therefore represent development stages which relate to different but long fire intervals. East–west river valleys south of the platform forests affect the flow of the main wind across the platform and prevented the development of the finger pattern south of Platbos, Lotteringbos, and Plaatbos.

The shapes or profiles of obstacles is also important (Barry, 1981). Sharp breaks of slope create more turbulence in the air passing over them than gradual slopes. Breaks of slope greatly increase the tendency for the airflow to separate from the ground and to form vertical eddies or rotors, i.e. air flow in a direction opposite to the wind direction across the barrier (Fig. 5). The intensity of the eddy increases with wind velocity across the barrier and with abruptness of the change in slope between the windward and leeward sides. Furthermore, air tends to flow round an isolated peak or range of limited length.

During a bergwind, air will flow upward in a northeasterly direction on the southern slopes of the southermost ridge above the platform forest. This explains the absence of forest on the southern slopes towards the western tip of the ridge (Fig. 3). Towards the eastern end the wind is calmer and the probability of a fire is smaller. Forest therefore often extends to below the ridge crest on the eastern end as in Platbos and Plaatbos.

With a steeper lee than windward slope, the lee eddy will prevent a fire from burning down the lee slope. Forests persist on such slopes to near the crest. Examples are the northern boundaries of Platbos and Plaatbos, and forests of the coastal scarp and river valleys which extend up to the sharp boundaries with the coastal platform.

An eddy does not develop with a very gradual change in slope such as a rounded hill. Winds will rather slow down towards the valley because of the rise of hot air at the fire front. Forests in such topographic situations are confined to valley bottoms such as many of the forests in the mountains where the ridges have been eroded to rounded crests near their ends (Fig. 6).

The diverse directions of the ridges and valleys in the mountains make wind flow patterns very complex. However, the presence of almost every mountain forest can be explained in terms of the wind flow patterns along the slopes and ridges surrounding the forest. Very often these patterns are evident as burnt strips in remnants of tall,

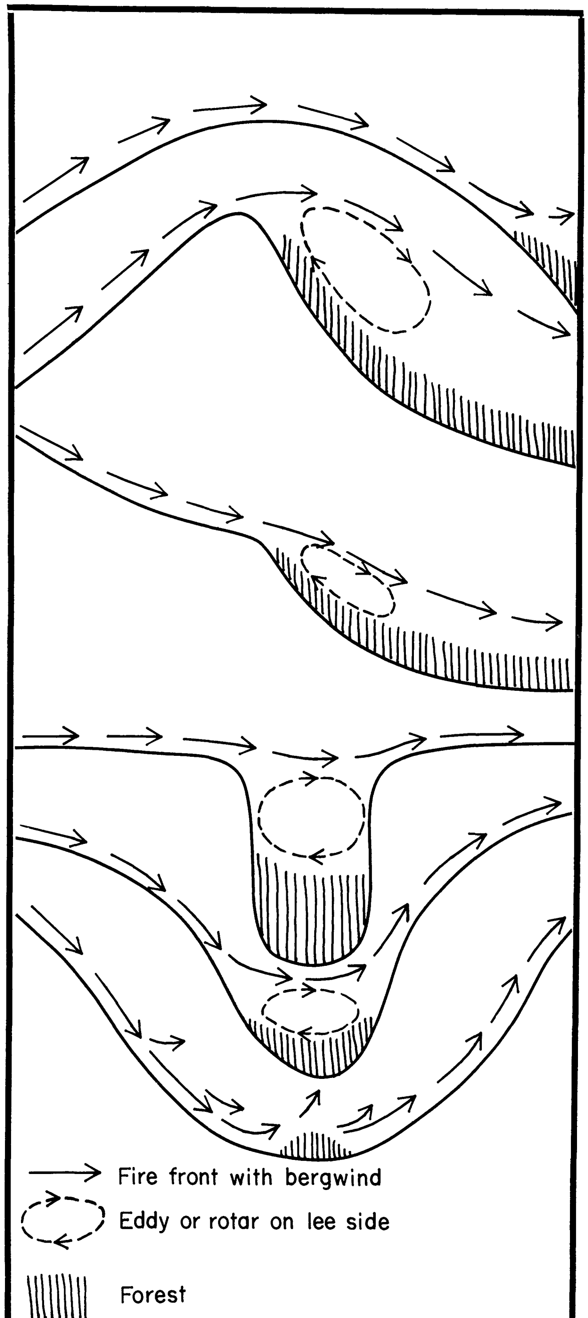

FIG. 5. Schematic view of hypothetical air flow across topographic barriers, the development of eddies on the leeside of the barrier and the persistence of forest in wind shadow areas. The figures are based on real examples from the study area.

unburnt fynbos indicating the path of previous natural fires. An example is the flow patterns around Buffelsbos along the Bloukrans river north of Platbos (Fig. 6). Sometimes relatively inconspicuous streams on either side of a forest, which grows on a slight ridge between the streams, provide enough protection to the forest in terms of wind flow patterns during a fire.

Bergwind fire frequency and rate of forest regrowth

The Witelsbos study area gives some indication of the process and rate of forest recovery. The density of *V. divaricata* seed which occur mixed with the charcoal suggest that a dense stand of this legume pioneer tree developed after the fire. *Virgilia* seed requires a very hot fire in order to germinate in large numbers and to develop dense stands (Phillips, 1926: personal observation and unpublished data). Although some seedlings of forest canopy species occur in such stands after about 5 years, they only become established after natural suppression and mortality and consequent thinning of the pioneer stand (C. Jacobs, personal communication, 1989). The mixed stand of 20 m in height in the Witelsbos burnt area must have established during such a succession.

Most of the forest canopy species can recover from fire by root, stem, or crown coppices (unpublished data). However, the two *Podocarpus* species cannot coppice and are killed by fire. The age of the older *Podocarpus* trees therefore provide a reliable estimate of the minimum period since the fire, i.e at least 230 years. This suggest that the age of the viable *V. divaricata* seed is about the same.

Recovery of forest therefore takes a long time. The composition of the canopy in the burnt zone of Witelsbos forest has recovered in terms of species content, but not in the relative density of the different species or the size class distribution of the individual species. The most significant difference is evident in the understorey. In the southern Cape many stands near the forest boundary, and also deeper into the forest, have understoreys which appear similar to the understorey of the burnt zone in Witelsbos and contain many pieces of charcoal (unpublished data). *T.*

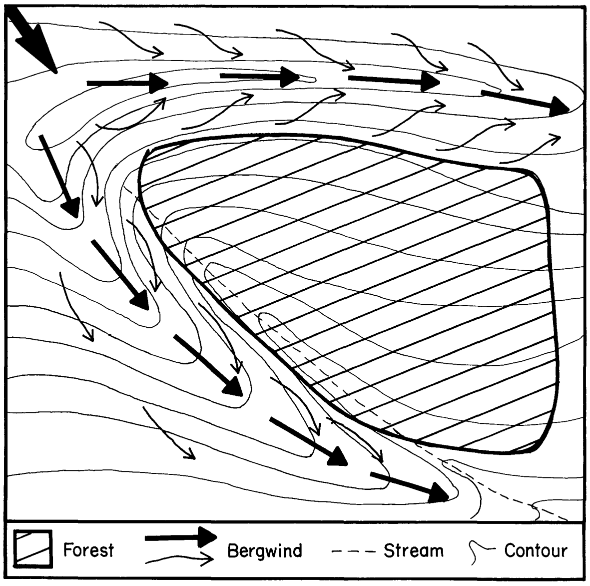

FIG. 6. Buffelsbos west of the Bloukrans river north of Platbos. The bergwind fire pattern is based on burnt strips of a natural fire through unburnt old fynbos near the forest margin.

crinitus is associated with the mature forest (Geldenhuys & Van Laar, 1980). It therefore takes centuries for a forest to recover after fire, to the stage with the tall, dense understorey of *T. crinitus.*

Evidence of the 1869 fire can be seen in portions of Koomansbos where the forest is shorter with abundant small stems, but not in the studied area in Witelsbos. Harison, conservator of forests in the area at that time, wrote that, except for the forest at Kwaaibrand, Koomansbos and Robbehoek near the coast, the forest escaped lightly (Phillips, 1963). The evidence of a fire at least 230 years ago and the historical record of the 1869 fire suggest that forest can persist with a fire interval of about 100 years. More frequent fires would cause forest to disappear and fynbos to persist. Fynbos would then increase the chances of frequent fires because of the density of flammable material (Van Daalen, 1981; Van Wilgen, Higgins & Bellstedt, 1990). The periodic, extreme, and devastating fires, such as the 1869 and earlier fires, caused great destruction of the forest and established their location pattern. More frequent but less intensive bergwind fires, such as the Kromrivier fire of 1984, must have maintained the open areas next to forest. These were repeatedly burnt by the local tribes and the early European settlers during hunting and for grazing (Phillips, 1963).

Bergwind impacts

Bergwinds act in two ways. Firstly, they desiccate the vegetation, particularly along their flow route through a valley and on ridges (Story, 1952). As such they affect the growth of the plants and increase their flammability. This effect is particularly severe on the more exposed ridges. Miehe (1989) mentioned a similar desiccating effect of the Himalayan föhn on forest community composition in the valleys of the northern slopes (similar to southern slopes in the southern Cape). The 1869 fire in the southern Cape followed a hot dry period of 6 weeks that reached a climax on the day of the fire with a scorching hot dry northerly bergwind and high temperatures that attained 34°C at 08h00 and 45°C at 14h00 (Edwards, 1984). The gusty nature of the wind causes the breaking of branches and leaves from tree canopies. On 2 June 1986, after a long period of successive bergwinds, a strong bergwind of mean speed of 32 km/h over a 6-h period caused a litter fall of 138 g/m^2 for June compared to the mean of 20 g/m^2 for May and July (Geldenhuys, 1988). Leaves of trees on the forest margins were scorched by the wind. The dry conditions which existed would have favoured the rapid spread of a fire if an ignition event occurred.

Secondly, if associated with an ignition, bergwinds drive the fire front to eliminate the desiccated forest vegetation. Usually the moist conditions of the forest site and closed community restrain the advance of fires originating outside the forest (Sim, 1907; Van Wilgen *et al.*, 1990).

Causes of bergwind fires

Humans and lightning are the main ignition sources for fires in the southern Cape (Le Roux, 1979; Horne, 1981). Anthropogenic fires are considered as the most important cause of bergwind fires (Sim, 1907; Phillips, 1963). Man has used fire in southern Africa since 1.0–1.5 million years ago (Brain & Sillen, 1988). Quartzite flakes of pre-Acheulean handaxe makers suggest hominid occupation around Plettenberg Bay during early Pleistocene (Butzer & Helgren, 1972). Although fire was used by communities of the Early Stone Age, it is possible that it was not widely employed until the succeeding Middle Stone Age (Hall, 1984). Some form of fire management of the vegetation for honey hunting, improvement of pastures for game hunting, and the farming of geophytes was practised for the last 125,000 years (Deacon, Hendey & Lambrechts, 1983). It is most probable that many intentional and accidental fires occurred during bergwind periods, as they occur under the modern use of fire in the management of vegetation (Le Roux, 1979; Horne, 1981).

Lightning is the most significant natural ignition source of veld fires in South Africa, although opinions differ on the frequency and importance of lightning induced fires in forests (Edwards, 1984). Lightning ignited a fire on a steep ridge in the Lottering forest in March 1984 during a relatively dry period with bergwind conditions. In the Diepwalle forest north of Knysna, most of the hilltops are either covered in fynbos, or carry sparse forest with fern understorey and contain scattered charcoal. Lightning frequently strikes these ridges during thunderstorms (W. J. Cooper, resident forester, personal communication, 1988). The fynbos 'islands' (Phillips, 1963; Cameron, 1980; Bond, Midgley & Vlok, 1988) have a northwest–southeast orientation which suggest that they have been created or maintained through a combination of lightning and bergwinds. Lightning induced fires burn relatively small areas because they usually strike near the ridges (Le Roux, 1979; Horne, 1981). Horne (1981) has shown that lightning fires occur in cycles and that human induced fires increased during periods of few lightning fires. Edwards (1984) suggested that in pre-colonial times with low population densities, lightning induced fires could have burned extensive areas, especially when they occurred under conditions favourable for fire. At present an effective fire prevention and combating system in the plantation areas and the different landuse systems on the coastal platform reduce the chances of extensive fires.

Conditions for lightning and bergwinds do not usually coincide (P. D. Tyson, personal communication, 1987). Although the peak periods of lightning and bergwind occurrence are widely separated, the time of the 1869 fire indicate the presence of severe bergwind conditions during February. I have observed a succession of lightning and bergwind periods around George during late summer, and the overlapping of such conditions during March 1989.

Wind-related forest location pattern in southern Africa and elsewhere

Most large-scale natural fires are associated with prevailing winds of a particular direction during the fire-prone periods. I suggest that the prevailing wind-fire pattern will explain much of the present location pattern of forests in southern Africa. In particular, the hot, dry bergwinds blowing from the interior are a phenomenon along the mountains and escarptment of the southern African coast (Tyson, 1964).

Forests to the west of Mossel Bay and east of eastern Tsitsikamma are small, few, and far between (Fig. 2). These areas coincide with a much wider and drier coastal plain. I have experienced, while driving through these areas, that southwesterly winds in the west and southeasterly winds in the east are relatively hot and dry whereas those same winds are cool and moist between Mossel Bay and eastern Tsitsikamma. I suggest that during pre-colonial times fires occurring in these areas were often driven towards the mountains from the coastal plains and eliminated forests except for sheltered valleys and gorges. This would also explain the relative absence of forest south of the foothills between Mossel Bay and George, and east of Witelsbos (Fig. 2). In the forested area the southwesterly and southeasterly winds often cause misty or cloudy weather with rain and reduce the probability of extensive fires. The Langeberg range west of Mossel Bay and the Kareedouw range east of Witelsbos are relatively narrow with very few southerly valleys running from the mountains. The strong bergwinds blowing across these ranges would cause an overturn of air on the lee side to form a deep, standing eddy (Barry, 1981). Fires originating in the valleys on the lee side would eliminate much of the forest on the exposed southern slopes. Between eastern Tsitsikamma and Port Elizabeth most mountain ranges reach the coast at an angle. The ranges are separated by wide valleys which form channels for the bergwinds or southeasterly winds which would carry winds (and fires) up and down those valleys and mountains.

Many forests along the eastern escarpment of southern Africa show location patterns which are typical of the bergwind shadow patterns of the southern Cape. Examples are Gudu forest in Natal Drakensberg and forests in Collins Pass area of northern Natal and in the Wolkberg/Serala area (Edwards, 1967, Photo 110, 116; Acocks, 1975, Fig. 77; Cooper, 1985, several photographs; personal observation).

Several studies in other parts of the world have related location patterns of forests to wind patterns or situations similar to those found in this study. Rowe & Scotter (1973) and Foster (1983) have found that strips of unburned vegetation occurred downwind of fuel breaks such as wetlands, water bodies, areas of bare rock or soil, and in relation to topography and variation in wind direction. Grimm (1984) found forest vegetation in Minnesota to be most strongly correlated with the fire probability pattern, which was a function of both abiotic and biotic factors. Rough topography caused more erratic wind movement, and slowed, divided and halted the advance of fire. Ash (1988) discussed the location patterns of rainforest in Australia. In temperate Tasmania rainforest occurred in gorges and gullies, the only habitats which usually escape fire. On hillsides with both rainforest and pyrophytic vegetation, rainforest occurred downslope, which was attributed to modification of fire behaviour by degree and direction of slopes. Where rainforest occurred upslope of pyrophytic vegetation, the upper parts of the ranges were dissected by valleys. Rainforest occurred in these valleys and its extent was controlled by steepness of the valley floor, the presence of rocks or cliffs, and the presence of tributary valleys.

Bergwinds and climatic change

Palaeoecological studies relate warm and moist periods with forest expansion and cool and dry periods with forest regression (e.g. Van Zinderen Bakker, 1976; Deacon, 1983; Deacon *et al.*, 1983). Forests do however persist in areas of relatively low rainfall (Rutherford & Westfall, 1986; Geldenhuys, 1991). This study has shown that forest persistence is mostly related to sheltering from regular fires, in particular bergwind fires. I suggest that because bergwinds are associated with particular atmospheric circulation patterns, they provide a useful key to the correlation of changes in forest area with climate changes.

Bergwinds conform to the general circulation over the sub-continent (Tyson, 1964). They occur in the region of increased pressure gradient between a high-pressure cell over the interior (plateau), and a depression or frontal system moving round the south coast of southern Africa. The high temperature and low humidity of bergwinds appear to be due to dynamic heating of subsiding upper air from the semi-permanent high pressure cell over the interior of southern Africa. Bergwinds are present in the winter months and absent in the summer months due to the different circulation patterns during the different seasons (Tyson, 1986). Goldammer & Siebert (1989) suggested for Eastern Borneo that interannual climate variability, associated with the 'El Nino-southern oscillation' phenomenon have an impact on drought stress and flammability and favour the occurrence of wildfires during such periods. From casual observation of local weather data, I have noticed that in some years more frequent and intense bergwinds are experienced, whereas during others bergwinds are almost absent. I suggest that this may also occur over longer time intervals with climatic change that will lead to periods of frequent bergwinds and retreating forest, and periods of absence of bergwinds with expansion of forest.

CONCLUSIONS

The topographic configuration of plateau, escarpment and coastal plain has a major influence on the persistence of forest. It confines the flow of the hot, dry bergwinds, and fires driven by them, and as such allows forest to persist in bergwind shadow areas. It compliments the findings of Feely (1986) who has shown that the forest-grassland mosaic of mountain and coastal areas and the grasslands of the central plateau in Transkei existed before the arrival of Iron Age farmers about 300 AD.

Forests can recover from episodic, extreme bergwind fires. Most forest species are adapted to low-frequency fires. The large platform and river valley forests contain large areas which are probably never disturbed by fire. By contrast most of the small mountain forests are probably sometimes destroyed by fire and are as such regrowth forests. This is suggested by the few tree species in the canopy, and only those which are able to survive fires. Their understoreys resemble the understoreys of platform forests which have been burnt, such as at Witelsbos, and they contain charcoal pieces. Geldenhuys & MacDevette (1989) used this gradient of fire frequency to explain the low richness of woody plants, the high richness of ferns, and the almost absence of epiphytes and vines in mountain forests, and the high richness of woody plants, vines and epiphytes in the platform and river valley forests of the southern Cape. The gradient of species richness over disturbance frequency supports the theoretical model of maximum landscape diversity with intermediate disturbance postulated by Suffling, Lihou & Morand (1988). This relationship between disturbance frequency and species richness should be considered in a phytosociological study of the southern Cape forests.

Results from this study suggest that a gradient exists of high fire frequency (and probably lower intensity) along the ridges and northern slopes, with a low frequency (and probable high intensity, see Kruger & Bigalke, 1984) in the valleys. It can be expected that forest and fynbos plants and other biota are ordered along these gradients according to their adaption to different fire frequencies and intensities. The most diverse mixture of pioneer (frequently burnt fynbos on the ridges) and mature forest (in wind-shadow sites) can be expected to occur under an intermediate fire disturbance regime (Suffling *et al.*, 1988), which follows the natural fire patterns under the present climate. In the current practice of block burns in the mountain catchments, fires are initiated along the upper ridges around a catchment (personal observation). Once these fires have progressed some distance down the slope, the circle of fire is closed by lighting fires in the bottom of the valley in order to burn upslope towards the ridges. I suggest that it is possible that this practice breaks down the diversity of species along the gradients to a more uniform composition throughout the catchment. The block burn system should be revised in order to achieve the management objective of maintaining the patterns of species diversity.

The results also have implications for the fire protection plans of commercial plantations. Plantations of pines and eucalypts have been planted in fynbos, i.e. mostly fire-prone sites. The current practice is to establish wide fire breaks in the mountains north of the plantations which are burnt on a short rotation. The fire breaks often threat the survival of rare fynbos plants. They are also very expensive to maintain. This study suggests that only a few key points need intensive protection against fire, i.e. where the valleys emanate from the mountains.

The intensive fire protection systems for plantations and the intensive agricultural use of the coastal foreland reduced the frequency and extent of fires. This elimination of fire and the shade provided by plantation stands favour the spread and wider establishment of forest species (Geldenhuys, Le Roux & Cooper 1986). It supports the views of several authors that frequent fires eliminate forest and induce secondary fire-adapted vegetation, which slowly return to forest once fire frequency is reduced (Ellis, 1985; Corlett, 1987; Masson & Moll, 1987; Turner & Bratton, 1987; Veblen & Markgraf, 1988). This succession process under plantation stands should provide keys to the control of plantation weeds.

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