Trees and their response to wind: mid Flandrian strong winds, Severn Estuary and inner Bristol Channel, southwest Britain

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CONTENTS

SUMMARY

The response of contemporary trees to strong winds (gale force and greater) is repeatable and well defined, as shown by field studies in southeast Britain after the October 1987 and January 1990 events, combined with a wide-ranging literature survey. It involves the general processes of windprune,

Phil. Trans. R. Soc. Lond. B (1992) **338,** 335–364
Printed in Great Britain

windsnap, windtilt and windthrow. Windprune depends on a range of physical and physiological mechanisms and leads to the loss of axial symmetry by a tree, especially where open-grown at an exposed site. Windsnap, windtilt and windthrow see the fall of a tree, as the result of either the breaking of the trunk or partial to full uprooting. Damage of this sort in a forest or woodland ranges from single trees, to scattered groups (swathes), to general devastation. In the main, perfectly healthy trees in youth or early maturity are affected by windsnap, windtilt and windthrow during strong wind events. Their fall-direction is readily established using the position of the rootball or snapped end of the trunk, the alignment of a broken trunk and stump, the taper of the trunk, the position on the trunk of relatively crowded branches (tree crown), and the position of the typically upward acute angle between branch and trunk. Contemporary trees overthrown by wind fall in a direction close to the wind. The variance of fall-directions in a sample due to a single wind event is observed to increase with the size of the woodland area from which the sample is drawn, but appears to become constant for sample areas in excess of 10^2–10^3 ha. Because this constant variance is relatively small, the mean fall-direction becomes, in contemporary woodlands and forests, a trustworthy indicator of the general direction of the strong wind which felled the trees.

Rooted peats of mid Flandrian age (*ca.* 6000–2500 conventional radiocarbon years) which include prostrate trees are widely present among the post-glacial estuarine silts exposed along the shores of the Severn Estuary and the inner Bristol Channel. The trees when overthrown appear in the main to have been perfectly healthy and in youth to early maturity. Oak and alder are the predominant species, and their fall-directions, as judged from the criteria listed from contemporary forests and woodlands, and measured at 18 horizons distributed over 14 sites, are highly coherent both locally and over the area as a whole. Using a model in which the variance of fall-directions observed for a single event is combined with a probability density for event mean directions, it appears that the trees fossilized in the peats were felled by strong winds which blew chiefly toward a range of directions from N.N.W. clockwise to S.S.E. A westerly zonal air-flow is indicated but, compared to the contemporary wind regime as measured at Avonmouth, the strong winds came from a wider range of directions than now, with a greater emphasis on both southerly and westerly to northwesterly blows.

1. INTRODUCTION

Wind directions of the geological past traditionally were measured only from areas where aridity ensured the formation of cross-bedded sand dunes (e.g. McKee 1979; Brookfield & Ahlbrandt 1983). For want of appropriate methods, almost nothing is known of wind patterns from non-arid sedimentary environments, which are just as areally extensive, and regional palaeoclimatological studies based on geological criteria are consequently being held back. Provided that the data are carefully constrained as to age, it would be particularly helpful to have an understanding of wind régimes during the last glacial–interglacial cycle.

This paper recounts an exploratory study aimed at developing a method for the elucidation of aspects of the wind régime in non-arid areas, using geological evidence from the post-glacial sediments of the Severn Estuary and inner Bristol Channel, southwest Britain. Two facts are exploited. Firstly, the post-glacial sea-level rise (Fairbanks 1989) permitted the accumulation of voluminous coastal and estuarine deposits which include rooted, tree-bearing peats. Secondly, as every woodsman knows, the overturning of trees by strong winds, generally in a direction close to the wind, is a normal forest process. The paper concisely reviews the response of contemporary trees to strong winds, sets out criteria for the fall-direction of overthrown trees, and outlines a methodology for measurement and analysis of fall-directions. The review is supported by studies of the response of trees in southeast Britain to the storms of 15–16 October 1987 and 25 January 1990. These findings, combined with knowledge of today's wind régime, are then applied to the gathering and interpretation of fall-directions from the mid Flandrian rooted peats present in the estuarine alluvium of the area. An insight is thereby gained into the strong winds that affected the inner Bristol Channel and Severn Estuary during an important epoch, overall of relative warmth, within the post-glacial period.

Some attempt has already been made to use fallen trees to indicate wind. Although others before him had noted and speculated upon prone trees in British peat deposits, Skertchly (1877) apparently was the first systematically to record and map the orientations of prostrate trunks, and to interpret these data in terms of wind régime. He concluded from these Fenland studies that the trees were felled by winds largely from the southwest. A similar wind direction was inferred by Bibby (1940) from trees in a post-glacial peat on the coast of north Wales. The trees in another bed, however, appeared to have been toppled by northeasterly storms. Wnuk & Pfefferkorn (1987) recently gave a brief account of late Carboniferous storm winds, as recorded at a single locality by fallen lycopods and pteridosperms. Many foresters and forest ecologists measured the attitudes of trees felled by modern and historical storms, chiefly in connection with studies of forest ecodynamics (Alexander & Buell 1955; Gratkowski 1956; Alexander 1964; Boe 1965; Henry & Swan 1974; O'Cinnéide 1975; Brewer & Merritt 1978; Falinski 1978; Uhl 1982; DeWalle 1983;

Robertson 1987*a,b*; Foster 1988*a,b*; Gastaldo 1990). The most wide-ranging of these, employing a questionnaire survey, concerns the October 1987 event in southeast Britain (Cutler *et al.* 1989, 1990). The wind-related malformation of trees is often exploited in studies of the prevailing air-flow (e.g. Jefferson 1904; Lawrence 1939; Putnam 1948; Holroyd 1970; Thomas 1973; Noguchi 1979; Robertson 1987*a,b*). Evidence of distortion is unlikely to be readily apparent in trees as preserved in peats, lignites and coals, but malformation in response to strong winds is almost certain to have occurred in ancient forests, affecting especially their margins and outliers.

2. RESPONSE OF CONTEMPORARY TREES TO WIND

(*a*) *Architecture of an ideal deciduous tree*

Emphasizing deciduous, broad-leaved species (Spurr & Barnes 1973; Wilson & Archer 1979; Zimmermann & Brown 1979), the ideal tree is formed architecturally of axially symmetrical underground and overground portions (figure 1*a*). The overground part consists of the trunk or stem, tapering very gradually upward, surmounted by the crown, composed of main branches dividing outward into thinner, lateral branches and, finally, leaf-bearing twigs. The flare is a short zone of rapid taper at the base of the trunk, commonly showing buttress-like upward extensions of the chief roots. Underground lies the root system, with perhaps some of the higher roots just breaking the ground surface. The network of outwardly branching lateral and feeding roots typically is flat-lying and parallel with the top of the soil (Cutler *et al.* 1989; Helliwell 1989). Their radial length invariably exceeds that of the projected crown, in some species by a factor of nearly four times (Gilman 1988, 1989; Cutler & Richardson 1989). Vertical elements – tap roots and droppers (Cutler *et al.* 1989) – are absent from many species and discouraged by thin soils. From the standpoint of mechanical stability, the root system can be thought of as having two parts. Innermost and attached to the trunk is the rootball or rootplate, that is, the roots (terminated by fractures) and associated subsoil and soil which remain fast to the trunk when the tree is either overturned by the wind or otherwise wrenched from the ground. Rootballs tend to be circular in plan, but are very variable in profile and relative thickness. The outer roots are those remaining beyond the rootball.

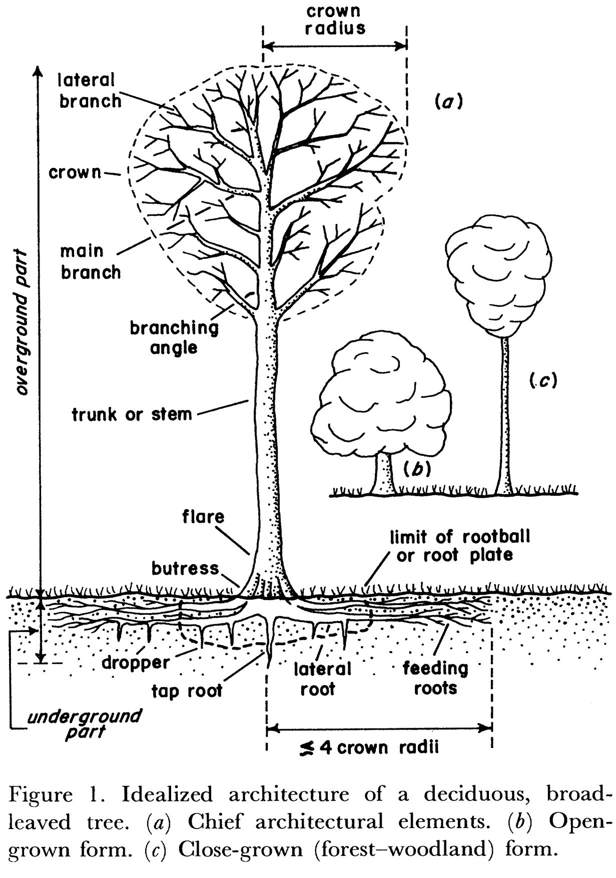

Figure 1. Idealized architecture of a deciduous, broad-leaved tree. (*a*) Chief architectural elements. (*b*) Open-grown form. (*c*) Close-grown (forest–woodland) form.

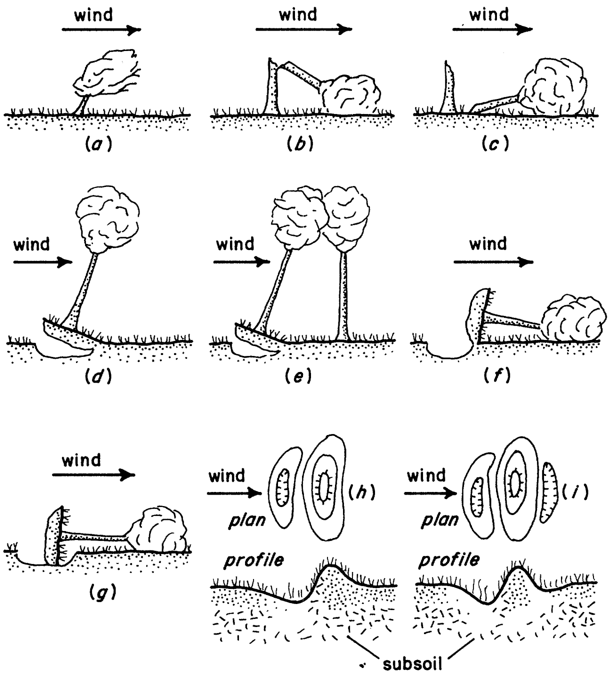

Figure 2. Types of wind-damage and related ground features. (*a*) Windprune. (*b*, *c*) Windsnap. (*d*, *e*) Windtilt. (*f*, *g*) Windthrow. (*h*, *i*) Mound-and-pit.

It is well recognized (Zimmermann & Brown 1979; Spurr & Barnes 1979; Mattheck 1990) that open-grown, broad-leaved trees (figure 1*b*) tend to be lower in height, with branches lower on the trunk and a larger and more spherical crown, than the same species in a dense forest (figure 1*c*). Forest trees, competing for light, are tall and slender of trunk, with a small, inverted-conical crown and few if any stem branches.

(*b*) *Types of wind damage*

As there is only the most general agreement about the response of trees to wind (e.g. Kennedy 1974; Savill 1983; Rottmann 1986), we here define four broad classes of wind damage (figure 2*a*–*g*), together with a distinctive ground-soil microrelief (mound-and-pit) indicative of one of these classes after all wood has decayed (figure 2*h*, *i*). We also recognize two sorts of collective response to wind.

(*c*) ***Windprune***

This general process results in the malformation of the overground portion of the tree, such that the crown loses axial symmetry, attains a lower than normal height, and has branches swept to leeward (figure 2*a*). Windprune includes both mechanical and physiological activities (Savill 1983; Robertson 1986). The first, most effective to windward, involves rubbing and impact between wind-stirred branches, twigs and leaves (e.g. Wilson 1980, 1984; Rushton & Toner 1989), damage to tender buds and shoots by rain, hail and snow particles, and the severing of twigs and branches, even occasionally main ones (e.g. Craighead & Gilbert 1962; Dittus 1985). The main physiological mechanisms are those of water stress (parching) to windward (Lawrence 1939), where wind speeds within the foliage are greatest, and the preferential growth of strengthening, cambial tissues in the trunk and larger roots to leeward (Mergen 1954). Near coasts, salt spray and even blown sand may further inhibit windward growth.

Windprune gives a distorted, asymmetrical form to open-grown trees (brushed and flagged trees) and a streamlined, wedge-shaped profile to canopies, in some forests repeated in waves (e.g. Tyrell 1983; Robinson 1987*a*). Windpruned trees are well known from coastal areas (Jefferson 1904; Owada 1973; Owada & Yoshino 1973; Thomas 1973; Noguchi 1979; Robertson 1986, 1987*a*,*b*), and from mountain districts (Lawrence 1939; Putnam 1948; Sekiguti 1951; Misawa 1954; Runge 1957, 1959; Holroyd 1970; Plesnik 1973; Yoshino 1973; Wade & Hewson 1979), where typically they reflect the local prevailing wind. Because of the uneven distribution of mass and roots, malformed trees will respond to strong winds from other directions differently to close-grown counterparts.

(*d*) ***Windsnap***

This process leaves roots unaffected but involves the breaking of the trunk at any height from within the flare upward to the base of the crown (figure 1). The break normally occurs within the crown in tall-crowned coniferous species. Two varieties are recognized.

In attached windsnap (figures 2*b* and 3), the break is incomplete, the upper part of the trunk remaining joined to the unaffected stem on the side toward which the crown fell. The range of modes of attachment is considerable (Mergen 1954; Webb 1958; Vignes 1969; Francis 1976; Falinski 1978; De Champs *et al.* 1982; Bouchon 1987; Canwell & Coutts 1988; Crampton 1988; Cutler 1988; Ogley 1988). The break is normally a more or less ragged fracture, but its orientation relative to the trunk can vary from orthogonal to finely oblique (figure 3). Only decay or the collapse of a neighbouring tree sees the release of the broken trunk and its fall to lie generally directly behind the stump. In other cases, the break is a complex of long fractures which parallel the grain, dividing the stem into a loose, flexible bundle of thick strands. Such trunks, as Gastaldo (1990) indicates, were clearly twisted, first one way and then the other, to the point of failure.

Figure 3. Mature silver birch involved in attached windsnap, Windsor Great Park (October 1987).

Detached windsnap (figure 2*c*) typically involves a slightly jagged, orthogonal break which normally leaves the separated trunk and crown prostrate on the ground and aligned downwind from the stump (Craighead & Gilbert, 1962; Fraser & Gardiner 1967; Kennedy 1974; De Champs *et al.* 1982; Despres 1987; Hall 1987; Angel 1988; Crampton 1988; Cutler &

Figure 4. Mature silver birch involved in free windtilt, Windsor Great Park (October 1987).

Gasson 1988; Danguy des Deserts *et al.* 1988; Ogley 1988; Fillon 1989; Grayson 1989). The broken ends seldom lie more than a few decimetres apart horizontally and in shape and size clearly are matched.

(*e*) *Windtilt*

This process involves the partial formation of a rootball, but the breaking of insufficient roots to permit the complete overthrow of the tree, because of either the brevity of the wind-force, the intrinsic strength of the roots and soil, or the support of a neighbour (figures 2*d*, *e* and 4). Many examples involving a wide range of species are recorded (Goodlett 1954; De Champs *et al.* 1982; Ogley 1987, 1988; Robertson 1987*b*; Crampton 1988; Danguy des Deserts *et al.* 1988; Foster 1988*a*,*b*; Cutler *et al.* 1989; Grayson 1989). The modest inclinations characteristic of free windtilt, generally less than 35° from the vertical, normally leave enough roots undamaged for the tree to survive and thrive again, mainly by throwing eventually trunk-like branches from upward-facing parts of the stem. An extreme leaning windtilt, however, generally means the early death of the tree, on account of the high proportion of severed roots.

(*f*) *Windthrow*

Windthrow sees complete uprooting (figures 2*f*, *g* and 5) and is a common response to strong winds (Wood 1970; Kennedy 1974; Bormann & Likens 1979; Guillery 1987; Ogley 1987, 1988; Cannell & Coutts 1988; Crampton 1988; Cutler 1988; Cutler & Gasson 1988; Cutler *et al.* 1989; Gastaldo 1990; Macmillan-Browse & Russell 1990; Brown & Keough 1992). The tree crashes in a few seconds prone to the ground, with many of the branches, especially to leeward, becoming smashed. Typically (Cutler *et al.* 1990; Gasson & Cutler 1990), the rootball has a radius measured over the ground of about 8 trunk radii (figures 5 and 6), with a range between 3 and 15, and displays severed lateral roots tilted into a near-vertical plane (figure 7). Cutler *et al.* (1989) point to considerable variation with species and age in rootball absolute radius. Depending on soil thickness and bedrock character, the rootball varies in cross-section from thin and parallel-sided to relatively deep and trapezoidal to plano-convex.

Figure 5. Small windthrown beech, Windsor Great Park (October 1987). Note positions of rootball and crown, taper of trunk, and branching angle as criteria of fall-direction.

Figure 6. Rootballs attached to mature, windthrown beech trees, Windsor Great Park (October 1987). Note buttresses on the flare of each tree and the severed roots around the edges of the rootballs.

Two forms of windthrow were observed after the October 1987 and January 1990 storms in southeast Britain. In hinged windthrow, mainly confined to saplings and to trees in shallow soils that enforce thin plate-like rootballs, the lateral roots to leeward bend but do not break (figure 2*f*). What we here call ball-and-socket windthrow (figures 2*g* and 7) is characterized by a deep rootball, typically positioned above the centre of the pit it had vacated. Such a tree either at failure had tended to rotate about an imaginary subhorizontal axis a short distance up the trunk or, on nearing the prone position, had slipped back into the pit vacated by the root mass.

(*g*) *Mound-and-pit*

The floors of North American natural forests were early recognized (Shaler 1892; Holmes 1893) to carry a widespread form of microrelief called mound-and-pit (Goodlett 1954; Stephens 1955, 1956; Denny & Goodlett 1956 1968; Lyford & MacLean 1966; Bormann *et al.* 1970; Brewer & Merritt 1978; Bormann & Likens 1979; Schaetzl 1986 1990). In Britain, Brown & Keough (1992) report sub-fossil occurences, and abundant examples can be seen on Minchinhampton Common near Stroud (Gloucestershire), where a whole wood had been felled during a storm in late medieval times. The ideal mound-and-pit (figure 2*h*, *i*) consists of a smoothly rounded, crescentic ridge associated with either a complementary hollow or a pair of unequal hollows. Typically, the features have a relief of several decimetres relative to the undisturbed forest floor, and attain a length up to a few metres. In practice, mound-and-pit of different ages occur together, but a prefered orientation may still be evident (Stephens 1956; Denny & Goodlett 1968).

Later workers have found no cause to doubt

Figure 7. Side view of the rootballs illustrated in figure 6, Windsor Great Park (October 1987). Note the plate-like character of the rootballs, the severed radial roots, and the scattered droppers.

Shaler's (1892) conclusion that mound-and-pit represents the degraded rootballs of windthrown trees. The primary soil horizons, like the root systems, are tipped into the vertical during windthrow (figure 2*f*, *g*). Evidence of this remains within the mound-and-pit (figure 2*h*, *i*), together with a subsequent pattern of gravitationally redistributed primary soil materials, and signs of renewed horizonation (Lutz & Griswold 1939; Lutz 1940; Denny & Goodlett 1956; Lyford & MacLean 1966; Armson & Fessendon 1973; Brown 1976; Beke & McKeague 1984; Schaetzl 1986, 1990; Schaetzl *et al.* 1986; Semeniuk 1986; Schaetzl & Follmer 1990; Small *et al.* 1990). Rootballs degrade very slowly and mound-and-pit can remain evident for up to many centuries (e.g. Stephens 1956; Thompson 1976; Schaetzl & Follmer 1990).

(*h*) *Swathes*

The October 1987 and January 1990 storms showed that strong winds will not only fell single trees scattered over a forest, but also bring down most if not all of the trees in comparatively small, dispersed areas here called swathes (figures 8 and 9*a*, *b*, *e*). Other reports show this type of collective response to be widespread and frequent (Stoeckeler & Arbogast 1955; Gratkowski 1956; Anderson 1964; Lyford & MacLean 1966; Wilson 1976; Bormann & Likens 1979; Somerville 1980; Uhl 1982; Ogley 1987, 1988; Fillon 1989; Dobson *et al* 1990).

Swathes vary from clusters of 5–10 neighbouring trees, occupying as little as 0.025 ha, to regiments of hundreds of specimens spread over up to 5 ha. In plan swathes vary from irregular but approximately equidimensional (figure 9*b*) to markedly elongated parallel with the wind (figure 9*e*). A herringbone pattern of overthrown trees is occasionally seen in elongated swathes (e.g. Ogley 1988), but the majority, regardless of shape, seem to display little or no internal patterning of fall-directions. Swathes can also result from the highly localized strong winds of tornados (Gastaldo 1990).

(*i*) *General damage*

The growth and merging of swathes creates a state of general damage, characterized by the fall of most trees over areas measuring many hectares (figures 8, 9*c*, *d*). In appearance, these areas closely resemble forests devastated by catastrophic volcanism (e.g. Foxworthy & Hill 1982) and other large explosions (Watson 1989).

Many storms affecting Britain have led to general damage. The October 1987 event (Ogley 1987, 1988; Forestry Commission 1988; Quine 1988; Cutler *et al.* 1989; Grayson 1989; Barrett *et al.* 1990; Crochet *et al.* 1990), which also devastated Britanny and Normandy (Danguy des Deserts *et al.* 1987; Sayer 1988; Fillon 1989), felled an estimated 15×10^6 trees in southeast Britain (figure 9*d*). Partly because of this extreme level of destruction, the equally if not more severe January 1990 storm (McCallum 1990; McCallum & Norris 1990; Hammond 1990) toppled a mere estimated 4×10^6 trees. Extensive general damage also resulted from the recent storms of 1953 (Steven 1953; Andersen 1954), January 1968 (Cannell & Coutts 1968), and January 1976 (Francis 1976). On the European mainland, extensive general damage arose in the Netherlands, Denmark and Germany during the storms of November 1972 and April 1973 (Kleinschmit 1974; Otto 1974), and in southeast France during the event of November 1982 (De Champs *et al.* 1982; Despres 1987; Guillery 1987*a*,*b*). Widespread general damage was caused in northeast France by the thunderstorm of July 1984 (Guillery 1987*a*,*b*). De Reure (1987) lists other damaging storms in France (see also Vignes 1968).

General damage has been widespread and frequent elsewhere. The September 1938 hurricane was disastrous for the New England forests (Curtis 1943; Foster 1988*a*,*b*). The line squall thunderstorm of July 1977 damaged 3.4×10^5 ha of forest in Minnesota and Wisconsin (see also Stearns 1949). A storm in October 1977 devastated more than 4×10^4 ha of forest in the Canterbury district, New Zealand (Wilson 1976). Anderson (1964) described the effects of a single squall or thunderstorm on the swamp forests of Borneo. The damage, affecting about 620 ha, was blast-like, with linear swathes radiating outward from a large, central zone of general destruction. Webb (1958), Craighead & Gilbert (1962), Wood (1970), Dittus (1985) and Semeniuk (1986) describe the effects of other tropical storms.

(*j*) *Ecological significance of windsnap, windtilt and windthrow*

These normal processes open up the forest canopy, not only at swathes and in areas of general damage, but even where just one tree fell, permitting affected tracts to be reseeded and encouraging understorey growth. Together mainly with wildfire, wind damage regenerates and compositionally rotates a natural forest (Bormann & Likens 1979; Hartshorn 1980; Foster 1988*a*,*b*), which at any instant appears as a complex mosaic of stands differing in age and, to some

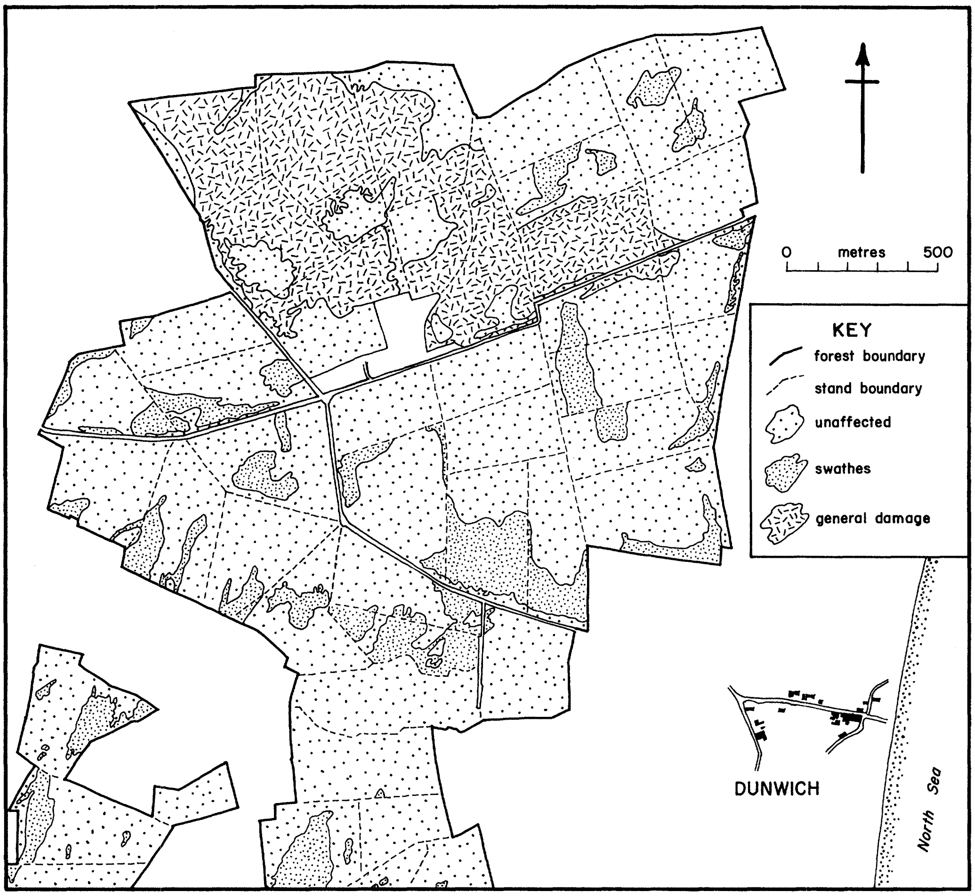

Figure 8. Distribution of swathes and an area of general damage due to the October 1987 storm in the northern part of Dunwich Forest, East Anglia. Data supplied by courtesy of the Forestry Commission.

extent, in species composition. The early recognition by Jones (1945), Stearns (1949), Stephens (1955, 1956) and Spurr (1956) of the ecological role of wind damage in particular has been amply substantiated by studies in the forests of Europe (Falinski 1978), North America (e.g. Henry & Swann 1974; Lorimer 1977; Brewer & Merritt 1978; Canham & Loucks 1984; Foster 1988*a*,*b*), Japan (Naka 1982; Kanzaki & Yoda 1986), and the tropics (e.g. Anderson 1964; Putz *et al.* 1983). The rate of site regeneration, however, is difficult to quantify but, depending on climate, a timescale of tens to hundreds of years does not seem out of the question.

3. MECHANICS AND FACTORS OF WINDSNAP AND WINDTHROW

(*a*) *Mechanical models*

The wind-induced failure of a tree, either by uprooting or the breaking of the trunk, which call for forces of a similar order, may be modelled mechanically at two levels. Static models are the simplest, but admit of no short term wind–tree interactions. Dynamic models, however, try to include effects due to the complex motions actually experienced by trees in the wind. All models suffer from the difficulty of specifying the force due to a wind that is gusty, that is, turbulent, on a timescale of seconds and a spatial scale comparable to trees themselves (e.g. Baldocchi & Meyers 1989).

Two static models for windthrow merit consideration. In one the rootball fails in shear (figure 10*a*), according to the equation

$$RF_{\mathrm{RS}} = aF_{\mathrm{V}} + bF_{\mathrm{TW}}, \qquad (1)$$

in which F_{RS} is the shear force over the underside of the rootball, F_{V} the wind force, F_{TW} the mass of the overground tree, a and b the lengths of moment arms with respect to the horizontal axis P, and R the radius of curvature of the underside of the (assumed sub-hemispherical) rootball. The weight of the rootball, F_{RW}, and the cohesion across its underside F_{RC}, create zero moment at P. Although many rootballs in shape fit the model, other field evidence, especially the rarity of slickensides beneath rootballs, indicates that failure is little influenced by the shear strength of the roots and soil. Rather, it is normal to observe a series of open, but closely spaced, ground-parallel, tensional fractures low in the rootball. Figure 10*b* presents a model which envisages the rootball failing in tension (Papesch 1974; Coutts 1986; Bouchon 1987; Blackwell *et al.* 1990), for which we may write

$$aF_{\mathrm{V}} = bT_{\mathrm{W}} + cF_{\mathrm{RW}} + cF_{\mathrm{RC}}, \qquad (2)$$

where c is the length of the moment arm pertaining to

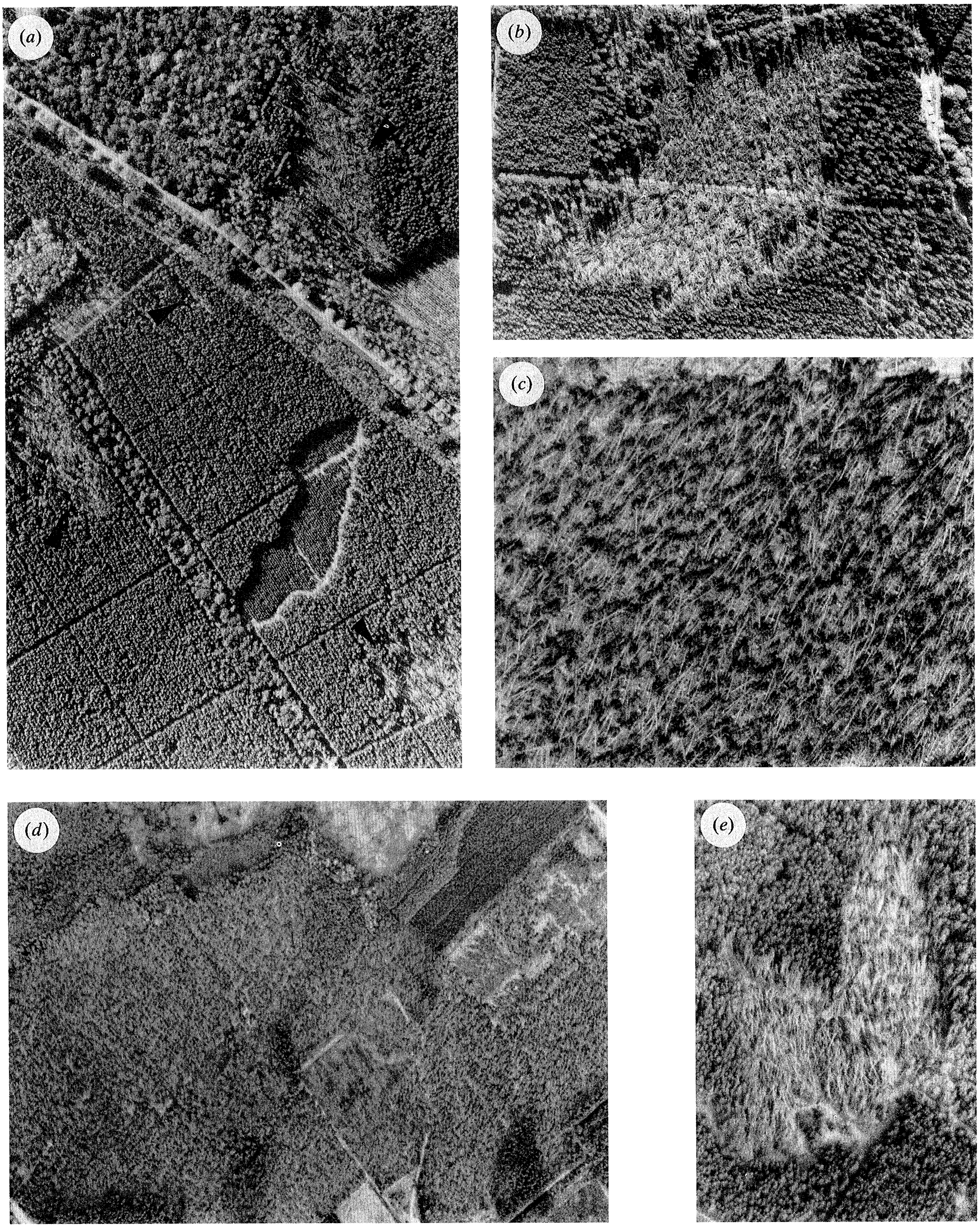

Figure 9. Wind-damage in contemporary woodlands (October 1987). (*a*) Four swathes (arrowed) and a replanted, older swathe, The King's Forest, Thetford (area 900 × 550 m; north toward bottom right; wind from top). (*b*) Oval swathe, The King's Forest, Thetford (area 500 × 400 m; north toward bottom; wind from top right). (*c*) Windthrown trees in part of an area of general damage. Dunwich Forest, Suffolk (area 400 × 375 m; north toward top; wind from bottom left). Trees appear pin-like, with white rootballs toward bottom left (upward). (*d*) Part of area of general damage, Dunwich Forest, Suffolk (area 1050 × 800 m; north toward top left; wind from bottom). Areas of wind-felled trees show in lighter tone. See also figure 8. (*e*) Two overlapping swathes, Dunwich Forest, Suffolk (area 250 × 200 m; north toward top; wind from bottom). MAFF photographs. Crown copyright reserved.

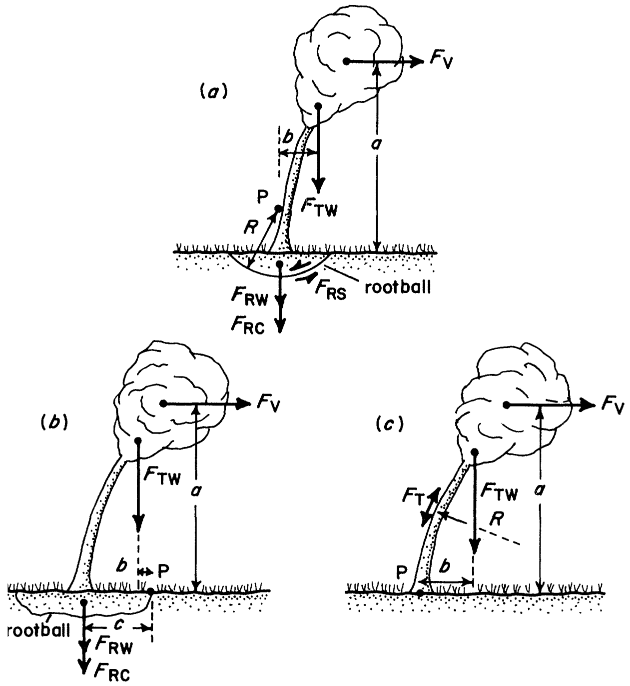

Figure 10. Definition diagrams for models of (*a*, *b*) windthrow, and (*c*) windsnap.

F_{RW} and F_{RC} about the hinge P. It may be appropriate to add as a further resisting force the bending moment of lateral roots at P. As F_{TW} and F_{RW} are each of order 10^5 N for a mature tree, the wind force at failure is also likely to approach this order.

Windsnap can be modelled statically (figure 10*c*) by imagining a tree to be a tapering beam cantilevered from the ground (Wilson & Archer 1979; Petty & Worrell 1981; Petty & Swain 1985; Morgan & Cannell 1987; Milne & Blackburn 1989). The moment of the tensile force in the trunk that resists the wind and weight forces is $F_T = \pi r^4 E/R$, where r is the cross-sectional radius of the trunk (measured at the same height as R), E the modulus of elasticity of the living wood, and R the minimum radius of curvature of the bent stem. Failure is governed by the equation

$$F_T = aF_V + bF_{TW}, \qquad (3)$$

in which a and b are the lengths of moment arms relative to the base of the trunk at P. Note that R becomes increasingly small, and F_T correspondingly large, as the turning forces increase and the tree bends more. At failure the tensile stress rE/R at the outer bent surface of the trunk just equals the breaking strength of the wood. For a mature tree, the bending moment at failure is of order 10^6–10^7 N m.

Dynamical models of windsnap and windthrow recognize that trees sway and twist considerably in the turbulent wind (Jacobs 1954; Sugden 1962; Mayhead 1973*a*; Oliver & Mayhead 1974; White *et al.* 1976; Holbo *et al.* 1980; Coutts 1983, 1986; Blackburn *et al.* 1988; Cannel & Coutts 1988; Mayer 1989), and that these motions are carried to the roots (Coutts 1983, 1986), progressively weakening the anchorage (Steven 1953; Hütte 1968; Coutts 1986). The forced sway period is typically a few seconds and lies close to the natural period, increasing with the age and size of the tree. The swaying tree extracts energy from the wind, not only because it offers form and frictional drag, the only components of the wind force recognized in static models, but also through inertia, the cyclic compression and stretching of woody tissues, and damping caused by entanglement with and rubbing against neighbours. The instantaneous dynamic load on the tree can be several times the static value (Blackburn *et al.* 1988), and it is not surprising that pulling tests do not correctly estimate the critical loads for failure (Blackburn *et al.* 1988; Cannell & Coutts 1988).

(*b*) *Factors influencing windsnap and windthrow*

Of the many factors that influence wind-damage to trees (Savill 1983; Robertson 1986*a*, 1987*b*; Rottmann 1986; Mayer 1989), the most important are: (i) the wind (strength, duration, gustiness); (ii) the tree anchorage (root system, soil, drainage); (iii) the terrain; and (iv) stand character (tree species, density, height). Some of these factors are interdependent. For example, rooting behaviour is partly determined by species.

It is strong winds that damage trees (see Rottmann 1986; Miller *et al.* 1987). Winds of gale force (mean speed 16.7–19.1 m s^{-1}), especially if persistent, cause windprune but do not commonly either overthrow or snap other than scattered trees. Windthrow and windsnap, with the damage becoming increasingly general, are chiefly the result of winds of severe gale (19.1–21.7 m s^{-1}), storm (21.7–24.1 m s^{-1}), violent storm (24.1–26.8 m s^{-1}) and hurricane (more than 26.8 m s^{-1}) force. These winds in temperate latitudes are chiefly associated with deep atmospheric depressions, but may also accompany convective storms, which can be extensive and persistent (Guillery 1987*a*,*b*). Strong winds in lower latitudes mainly accompany hurricanes, typhoons, line squalls and thunderstorms.

The contemporary wind-climate of the British Isles has been much studied (Thomas 1960; Harris 1970; Hardman *et al.* 1973; Shellard 1976; Smith 1983; Cook & Prior 1987; Davies *et al.* 1988; Hammond 1990). It is largely determined by the passage eastward across the Atlantic Ocean of depressions on a substantial range of tracks (figure 11*a*) (Thomas 1960; Cook & Prior 1987; McCallum & Norris 1990). Strongest on average during January, the wind is more severe in Ireland and western Britain than in the interior (Shellard 1976; Cook & Prior 1987). In the Bristol Channel and Severn Estuary today, the hourly mean wind with a 50-year return period is of storm force, and the 50-year gust speed 42–48 m s^{-1}. Gusts record the passage of individual turbulent eddies, lasting up to several seconds, and their extreme gust speeds are typically 1.75 times the mean hourly wind (Burt & Mansfield 1988). Although the extreme gust speed declines inland, the gustiness of the wind increases owing to the enhanced ground roughness (Gloyne 1968; Shellard 1976). In comparison with gentle winds (Baran 1992), little is known of the

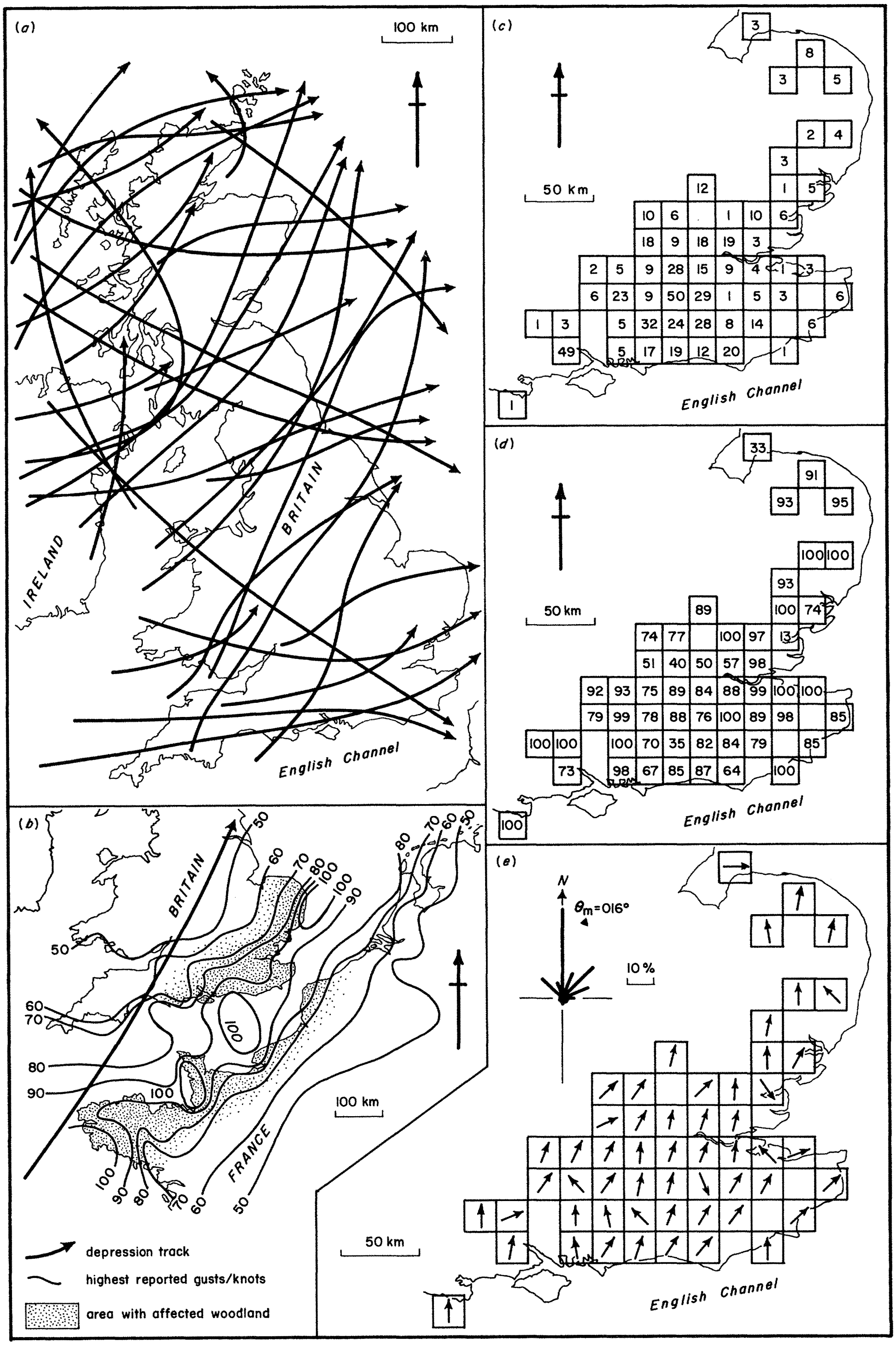

Figure 11. The October 1987 storm and its effects in the woodlands of southeast Britain and northwest France. (*a*) The tracks of deep depressions affecting the British Isles over a 10-year period (after Cook & Prior 1987). (*b*) Track of centre of October 1987 depression (after Grayson 1987) and distribution of highest reported gust speeds (Burt & Mansfield 1988). (*c*) Distribution by 20-km squares of reported numbers of orientated wind-felled trees. (*d*) Distribution by 20-km squares of vector strength (in percent) of orientated wind-felled trees. (*e*) Vector mean fall-directions of orientated wind-felled trees by 20-km squares and grand summary (raw data for *c–e* supplied by Dr D. F. Cutler of the Tree Root Survey, Royal Botanic Gardens, Kew; see also table 1).

gustiness of strong air flows, and more research is needed on this topic.

Unusual as was its climatological background (Namias 1989), the 15–16 October 1987 storm which affected northwest France (Danguy des Deserts *et al.* 1988; Fillon 1989) and southeast Britain (Advisory Services Branch 1988; Burt & Mansfield 1988; Templeman *et al.* 1988; Woodroffe 1988; Grayson 1989;

Barrett *et al.* 1990; Crotchet *et al.* 1990; Shutts 1990) is otherwise quite representative. The intense depression followed a north-northeasterly track (Burt & Mansfield 1988; Grayson 1989) and, as with other tree-damaging storms (Grayson 1989), the strongest winds lay to the right of this path (figure 11*b*), as dictated partly by the southward decrease in the Coriolis force. Along the English Channel, roughly coincident with the strongest winds, the return period of the mean hourly wind speed exceeded 200 years, and extreme gusts in excess of 51 $\mathrm{m\,s^{-1}}$ were recorded (figure 11*b*) (Burt & Mansfield 1988; Fillon 1989). Winds of comparable strength, affecting a wider area, accompanied the storm of 25 January 1990 (McCallum 1990; McCallum & Norris 1990; Hammond 1990).

The soil and its drainage strongly influence the susceptibility of trees to strong winds. Windthrow appears to be predominate over windsnap in natural moist forests (Boe 1965; Hartshorn 1980), forested swamps (Stoeckeler & Arbogast 1955; Anderson 1964), and in forests after exceptional rainfall (Foster 1988*a,b*). In dry forests, windsnap tends to exceed windthrow (Naka 1982; Uhl 1982; Kanzaki & Yoda 1986). Windsnap also exceeds windthrow on the well-drained soils of some eastern North American forests and in Central American moist forests (Putz *et al.* 1983). Windthrow is generally the more important in the planted forests of the British Isles and continental Europe (Day 1950; Andersen 1954; Fraser 1962 1965; Alexander 1964; Pyatt 1966, 1968; Fraser & Gardiner 1967; Hütte 1968; Holtam 1971; Kennedy 1974; Cutler *et al.* 1990). Here, shallow-rooted trees on sandy or peat soils, and on thin, ill-drained substrates, are more susceptible to strong winds, failing almost exclusively by windthrow, than when deeply rooted on thick, well drained soils, which favour windsnap. The latter is certainly favoured by the artificial deepening of soils (Somerville 1980).

Terrain exerts a complex and subtle influence on wind-damage. Kennedy (1974), for example, found that the most susceptible trees were those growing on poorly drained level to gently sloping ground. The surface wind tends to follow ground contours, thus deviating from the airflow at a great height, and may become funnelled along valleys and between hills (Hütte 1968), making mountainous areas a common location for wind damage (e.g. Dobson *et al.* 1990). Because of incipient flow separation – the breakaway of the airstream where the ground abruptly changes downward in slope (Chang 1970) – the wind tends to be most variable and gusty to leeward of ridges and over the sheltered sides of valleys (Gratkowski 1956; O'Cinnéide 1975).

The influence of stand character has many sources. Open-grown trees, with their squat form (figure 1*b*) and thickened tissues due to constant wind-working (Jacobs 1954), are less susceptible to strong winds than the same species forced upward in dense stands (Alexander 1964; Wilson 1976). As regards close-grown trees, those seemingly most at risk are in late youth or early maturity (Curtis 1943; Andersen 1954, 1964; Alexander 1964; Kennedy 1974; Brewer & Merritt 1978; Putz *et al.* 1983; Foster 1998*a,b*). Too close a spacing in a stand appears to increase the risk of damage (Blackburn & Petty 1988). The wind works at gaps in the forest canopy and at the margins of stands, especially the sides facing the wind (Curtis 1943; Andersen 1954; Gratkowski 1956; Alexander 1964; Fraser 1964; Boe 1965; Wood 1970; Wilson 1976; Somerville 1980; DeWalle 1983). At these places, where the boundary beneath the wind changes in shape, powerful vortices and eddies can arise (e.g. Alexander 1964; Bergen 1975; Miller *et al.* 1991*a,b*), and the wind in force can penetrate below the canopy (Reifsnyder 1951; Alexander 1964; Fraser 1964; Raynor 1971; Mayhead 1973*b*; Li *et al.* 1985, 1991; McNaughton 1989). Swathes, for example, are commonly initiated at canopy gaps and upwind margins (figure 8). Species composition exerts its influence partly through rooting behaviour (shallow or deep) and partly through tissue strength. Shallow-rooted species like pine and beech are greatly at risk from windthrow (e.g. Andersen 1954). Generally, soft-wood species like conifers are more prone to windsnap than hardwoods (Boe 1965; Wood 1970; Falinski 1978; Putz *et al.* 1983; Foster 1988*a,b*). In a tropical forest, Craighead & Gilbert (1962) found very considerable between-species variation in resistance to storm winds. The aerodynamic drag of trees varies with leaf properties and consequently with species. Forms with large abundant leaves, having larger drag coefficients than species with small or sparse leaves (Mayhead 1973*b*), are the most prone when in leaf to wind damage (see equations 1–3). It may be inferred from L. H. Allen's (1968) work that the susceptibility of trees declines significantly after leaf fall, other factors remaining unchanged.

4. TREE ORIENTATION AND WIND DIRECTION

(*a*) *Criteria for the orientation of wind-felled trees*

Wind-felled trees either lean or fall in the general direction of the contemporaneous wind and even major branches detached during windprune tend to fall with the wind. Hence the felled tree has an azimuthal orientation which stands proxy for the wind itself. The axis (Cheeney 1983), that is, the elongation of the fallen trunk or branch, denotes the line of the wind. The polarity of the axis, that is, its direction (Cheeny 1983), gives the sense of air flow.

The fall-direction of a trunk or branch may be established from the position of one or more of: (i) the rootball; (ii) the broken end of the trunk, with or without the matching stump; or (iii) the crown with its many, closely spaced branches. The fall-direction of a trunk or branch may also be determined from: (iv) the sense of taper, especially at the flare; and (v) the relative position of the acute angle between branch and stem, lying upward toward the crown in most species. Where a fracture exposes the interior of the trunk, the angle may be defined by an oblique knot.

(*b*) *Measurement and analysis of tree fall-directions*

Using a good-quality hand-held magnetic compass, and standing on the trunk or branch, the axis or fall-direction can generally be measured to better than 5°. Most difficulty is experienced with irregular stems and branches, when it becomes necessary, with some risk of additional error, visually to average their orientation.

A sample of fall-directions measured at a site or over a region may be portrayed graphically in two main ways. Small samples (not more than 10 observations) are best depicted as a ray diagram, that is, a compass card on which the observations are plotted individually. It is better with large samples to group the data and plot them either as a rose diagram (circular histogram), with the frequency represented by the sector area (Nemec 1988), or as a spoke diagram, with the spoke length proportional to the number of observations. Here we as far as possible follow meteorological convention and plot grouped orientations as spokes on a twelve-sector (30°) compass card with sectors divided by the cardinal points.

The statistical analysis of circular orientation data (Mardia 1972; Cheeney 1983) assumes that the data are vectors, and it is conventional (the position adopted here) to give the data a uniform (unit) weight. The parameter which describes the central tendency of a spread of directions totalling n is the (vector) mean, θ_m. A number of parameters describe spread. The most fundamental is R, the mean resultant vector, or vector strength, calculated either as a fraction or percentage. The circular variance $S=(1-R)$, where R is the fractional value, and declines as the data cluster more closely about the vector mean. As Mardia (1972) explains, either R or S may be converted into the circular standard deviation, σ_θ (radians, degrees arc). Several theoretical probability densities are available to model the distribution of a circular random variable (Mardia 1972), of which the rather similar von Mises and wrapped normal distributions best represent natural spreads. Clustering in the von Mises distribution is described using the concentration paramer $\kappa \geqslant 0$, related to R and σ_θ. The distribution is uniform at $\kappa=0$ but becomes more concentrated about the mean as κ increases. Of a von Mises and a wrapped normal distribution of the same κ, the former is the more peaked. A test of randomness should be applied to an observed circular distribution (Mardia 1972). The most appropriate geologically is the Rayleigh test (Curray 1956), yielding for a sample of size n and vector strength R a probability p that the distribution is of random origin.

(*c*) *Sources of variance in tree fall-directions*

Only in a statistical sense do trees fall in the direction of the general wind. Any sample of fall-directions representing a single wind event will possess a certain variance, with contributions from up to five sources: (i) temporal and spatial changes in the mean wind-direction; (ii) deviations in gust direction from the local mean wind; (iii) a tendency of trees to fall downslope; (iv) lack of axial symmetry in the distribution of wind and resistive forces over individual trees (stem, root system, soil); and (v) tree interactions. A change in the direction of the local mean wind results from veering or backing during the course of a gale or storm. So far as British wind-felled trees are concerned, the change is most likely to record veering, noting again that the severest damage occurs mainly to the right of depression tracks (Grayson 1989). During the October 1987 storm, for example, the wind in southeast Britain veered from south to southwest (Burt & Mansfield 1988). The accompanying gusts deviated at times by up to 50° from the mean wind (Burt & Mansfield 1988). The few seconds that these last are probably all that are required for the actual felling of a tree, to judge from my observations during thunderstorm outflows, whether or not there had been prior weakening of the anchorage (Steven 1953; Hütte 1968; Coutts 1986). Substantial deviations from the general track of a storm, and the general direction of tree fall, can also occur where the vortex of a tornado touches down (Gastaldo 1990). Theoretically, windthrown trees are more likely to fall downslope of the wind than upslope, because a hinge sited on the downslope side of the rootball enhances the moment of the wind force. Only one kind of tree-interaction is at all significant. A close-grown windsnapped or windthrown tree commonly brings down some of its neighbours (domino effect), as is clear from the way the trunks and branches become entangled, but the stems generally fall over a spread of directions. Of minor importance is the fact that a windtilted tree has a distribution of weight lying off the centre of the rootball, rendering it liable to fall anomalously during the next event.

It is likely, therefore, that the variability of fall-directions observed from a single wind event will increase with the sample area. Figure 12 and table 1 confirm this for the October 1987 and January 1990 storms, but suggest a strong nonlinear relationship. For coverages greater than 10^2–10^3 ha, the variability is essentially independent of area. The samples (all available wind-damaged trees) from Ipsden Woods (figure 13*a*) and Green Dean Wood (figure 13*b*) come from plantations respectively of mature larch (*Larix*) and beech (*Fagus*) on thin, dry, clayey soils overlying Chalk. Only about 7% of the trees in each case were windsnapped, the remainder being windthrown and a very few windtilted. The area point-sampled from an air photograph of the northern part of Dunwich Forest (figure 13*c*), partly shown in figure 9*d*, bore a range of coniferous stands on sandy to gravelly soils. Only windthrown trees with clearly identifiable rootballs were measured. Two woodland areas were haphazardly point-sampled in Windsor Great Park (figure 13*d*). The samples represent chiefly mature trees, of a wide range of broad-leaved and coniferous species, growing on relatively wet clayey to sandy soils, derived from Tertiary sediments. Respectively 7% (all conifers) and 3% (a solitary birch) of the trees were windsnapped, the remainder being windthrown.

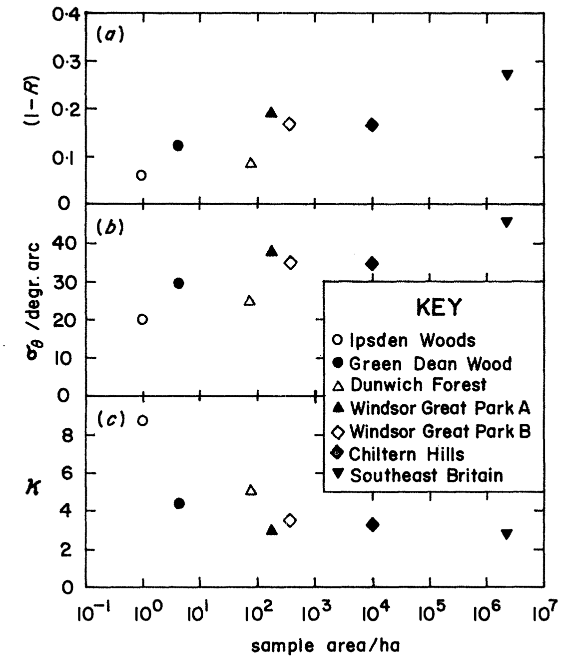

Figure 12. Measures of variance in the fall-direction of trees felled by a single event (October 1987 or January 1990), as a function of sample area. (See also table 1).

Planted woodlands in the western Chiltern Hills (Tilney-Bassett 1988) between Reading and Watlington were sampled at a density of 6–8 fall-directions from each of 25 2-km squares (figure 13*e*). The trees, growing mainly on thin gravelly to clayey soil overlying Chalk, are chiefly mature beech, but with some cherry (*Prunus*), birch (*Betula*), oak (*Quercus*), larch, fir (*Abies*) and spruce (*Picea*). Most were uprooted, but some 9% had snapped, the subsoils and soils being relatively very dry at the time.

The raw data for southeast Britain (table 1) were generously supplied by Dr D. F. Cutler (Royal Botanic Gardens, Kew) from his questionnaire-based Windblown Tree Root Survey (Cutler *et al.* 1990, A Forms). These came from local observers, who reported fall-directions nominally according to a 16-point compass card (some used only an eight-point scheme), in contrast to my own practice. Figure 11*c* shows the number of directions reported from each 20-km square of the affected area. In order to minimize an obvious excessive geographical bias in the data as supplied, I have considerably reduced on a random basis the observations analysed in a quadrant (British National Grid TQ 17) of one particular square. The fractional mean resultant vector by squares is comparatively high (figure 11*d*). Judging from the corresponding vector means (figure 11*e*), the tree-felling wind was quite uniform over southeast Britain. The summary spoke diagram (figure 11*e*) is much less peaked than that of Cutler *et al.* (1989), because of the steps taken to reduce excessive geographical bias, but some sectors are clearly over-represented through the partial use of the less precise eight-point card.

5. OCCURENCE OF MID FLANDRIAN TREES

(*a*) *Geological setting*

The sub-fossil trees discussed here are exposed on the shores of the inner Bristol Channel and Severn Estuary within a thin sequence of minerogenic and some organogenic sediments of post-glacial age and chiefly estuarine origin. The sequence partly infills a broad valley, widening to the southwest and then the west, with an undulating bedrock floor into which the Severn and its tributaries cut deep gorges (Codrington 1898; Hawkins 1962; Anderson & Blundell 1965; Anderson 1968; Williams 1968) during a probably Devensian lowstand of the sea (figure 14*a*, *b*). Various processes fashioned the valley floor. Judging from the presence of buried beach gravels (Andrews *et al.* 1984), the bedrock surface in the outer estuary was

Table 1. *Statistical summary of fall-direction of trees brought down during two recent storms*

site	event	area (ha)	*n*	θ_m (deg)	*R*	σ_θ (deg)	κ	*p*
Ipsden Wood, Oxon. SU 679831[a]	25 Jan. 1990	1	41	077°	0.940	20.1°	8.68	10^{-20}
Green Dean Wood, Oxon. SU 6878	25 Jan. 1990	4.5	85	097°	0.877	29.3°	4.40	10^{-20}
Dunwich Forest, Suffolk TM 4572, 4672, 4772, 4571, 4671	15-16 Oct. 1987	77	275	018°	0.913	24.5°	6.06	10^{-20}
Windsor Great Park (west), Berks. SU 9569, 9669, 9568, 9668	15-16 Oct. 1987	161	42	039°	0.808	37.6°	2.98	10^{-10}
Windsor Great Park (east), Berks. SU 9670, 9770, 9769, 9869	15-16 Oct. 1987	246	31	036°	0.832	34.8°	3.34	10^{-10}
Chiltern Hills, Oxon. SU 7092, 6890, 7090, 6788–7188, 6586–7186, 6584–7184, 6382–6982, 6280–6880, 6678–7078	25 Jan. 1990	10^4	180	083°	0.833	34.7°	3.38	10^{-20}
Southeast Britain TF, TG, SP, TL, TM, SU, TQ, TR, SY	15-16 Oct. 1987	2.2×10^6	580	016°	0.729	45.5°	2.80	10^{-20}

[a] British National Grid Reference.

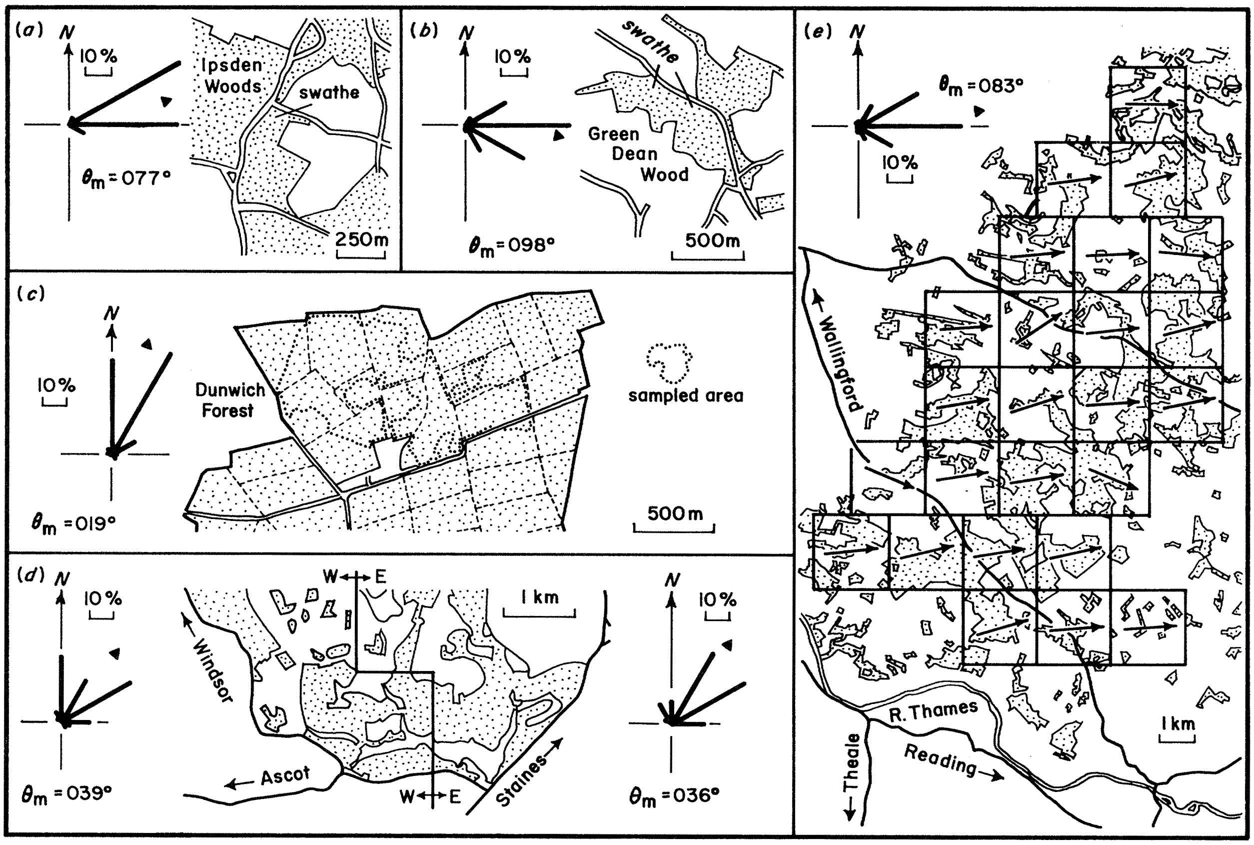

Figure 13. Summary of fall-directions of wind-felled trees (see also table 1). (*a*) Ipsden Woods (January 1990), south Oxfordshire. (*b*) Green Dean Wood (January 1990), south Oxfordshire. (*c*) Dunwich Forest (October 1987), Suffolk. (*d*) Windsor Great Park (October 1987), Berkshire. (*e*) Vector means by 2-km squares and grand summary, western Chiltern Hills (January 1990), south Oxfordshire.

partly shaped by marine processes. The bedrock surface in the middle and inner estuary carries widespread evidence of periglacial processes (ice-wedge casts, involutions, blockfields, patches of head) (Allen 1984, 1987), and locally supports thin, minerogenic to peaty soils.

The post-glacial deposits overlying the bedrock are described either from outcrop or boreholes in very many local publications, and only brief, general reviews are so far available (Allen 1990 1992). As Sollas (1883) glimpsed, it is nonetheless possible to recognize a standard sequence of post-glacial estuarine alluvium applicable with only minor local variations over the entire inner Bristol Channel and Severn Estuary (figure 14*a*). The sequence, approximately 10–15 m thick, begins either with thin gravels or sands or with a tree-bearing rooted peat (basal peat) which grades up out of the soil mantle. The overlying beds are chiefly estuarine sandy silts with locally some thin sands. These grade up into grey-green silts and clayey silts which, over a vertical range of several metres commencing at about Ordnance Datum, are interstratified with as many as five rooted peats and other organic-rich beds (e.g. Hawkins 1968; Kidson & Heyworth 1976; Murray & Hawkins 1976; Andrews *et al.* 1984; Brown 1987; Hawkins *et al.* 1989). Outcrops of these organic deposits, tending to occur as intertidal ledges, are indicated in figure 14*b*. The peats interstratified with estuarine silts – it is convenient to distinguish these as the 'included peats' – at many places visibly spring from the basal peats, which are strongly diachronous and have a wider altitudinal range (figure 14*a*). As exposed on or near the coasts, the included peats and corresponding basal peats range in age from 6100 conventional radiocarbon years before present (BP) to 2180 years BP (figure 14*c*), judging from dates assembled by Godwin & Willis (1964) (1), Hawkins (1971) (7), Murray & Hawkins (1976) (9), Heyworth & Kidson (1982) (26), Allen & Rae (1987) (1), and Smith & Morgan (1989) (15). Probably younger peats, in sequences up to 3 m thick, are present near the upland margins of the wider outcrops of estuarine alluvium (e.g. Caldicot Level, Gwent).

(*b*) *Environmental setting, mode of occurence, species and age*

Detailed botanical investigations were not attempted but, judging from the macroscopic evidence, at least four broad environments are represented by the peats: (i) moist woodland, characterized by much woody debris, abundant stumps and prostrate trunks; (ii) fen carr, typified by comparatively small trees, either dispersed or in clumps, accompanied by the remains of reeds and sedges; (iii) reed swamp, dominated by reed debris and detritus settled in shallow

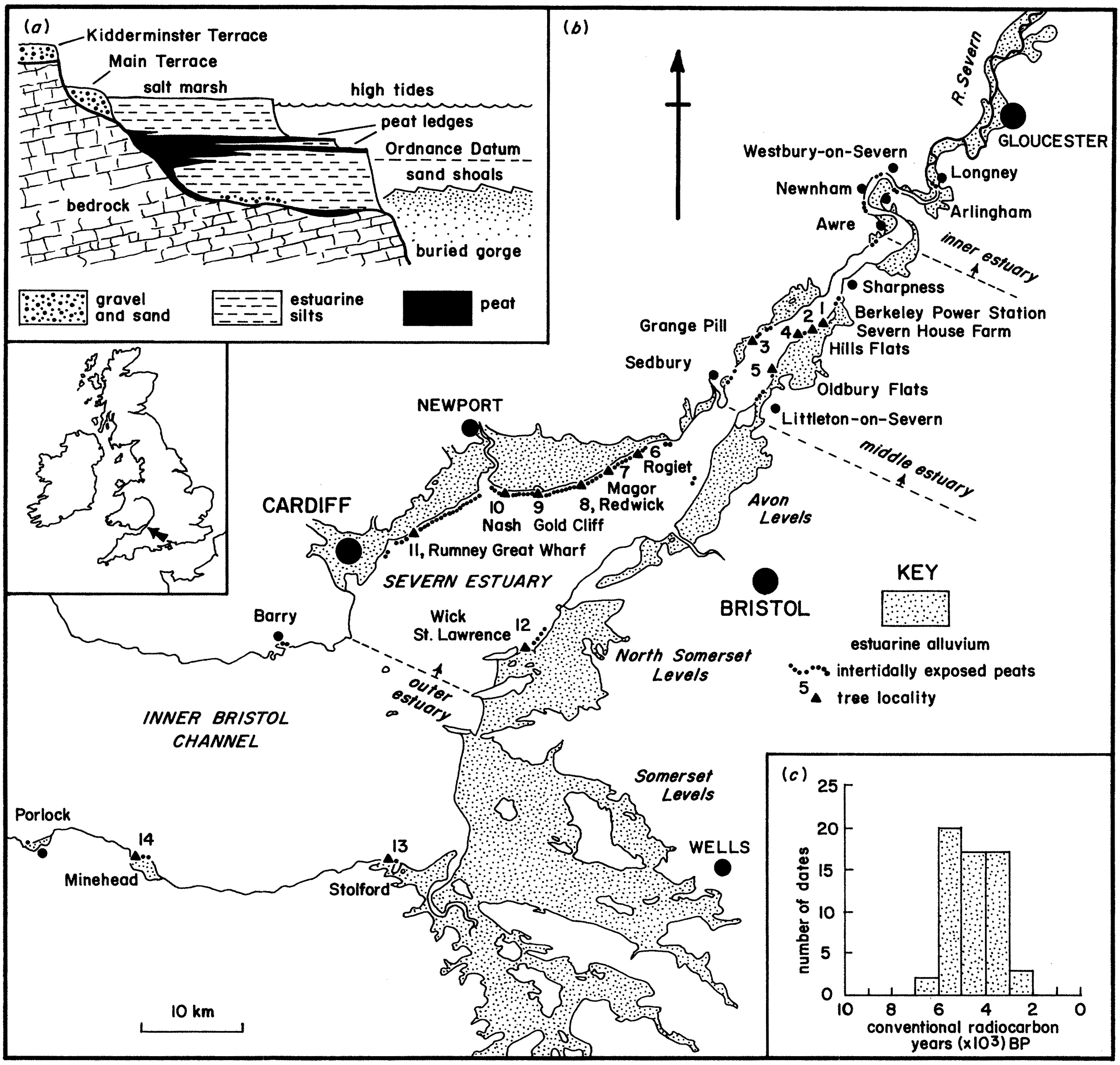

Figure 14. Severn Estuary and inner Bristol Channel. (*a*) Summary of late Pleistocene and post-glacial geology. (*b*) Occurence of post-glacial peats exposed intertidally and of localities at which wind-felled trees in the peats were sampled. (*c*) Frequency distribution of radiocarbon ages from 59 mid Flandrian peats (see text for details and sources).

ponds and lagoons; and (iv) raised bog, characterized by mosses in cushion-shaped masses. The included peats thin and divide away from the bedrock margins and 'islands' and include woodland peats (with fen carr, swamp and raised bog) only within a few kilometres of these eminences. Further out fen-carr peats predominate, and beyond these only reed-swamp deposits are found. The thinnest organic beds are organic-rich silty clays no thicker than a few centimetres which overlie rootlet horizons.

The trees sampled from the included and higher basal peats occur chiefly as stumps surmounting shallow root systems and as prostrate trunks, very many with rootballs, accompanied by much general debris, in the form of branches, including major ones, and twigs (figure 15). Erosion at the outcrop has in many cases picked out the details of root systems and, in a few instances, something of the pattern of branching. Prostrate trunks have generally lost their bark on the upper surface to erosion (it is normally detectable where peat or silt remains to be removed), and may be exposed to the heart, revealing knots where branches had sprouted. Hollow trunks and stumps infilled with sediment are very rare.

The woody tissues are very well preserved, and almost exclusively of healthy appearance. It is clear from a hand-lens inspection in the field that at most localities oak, recognizable by the characteristic rays in the wood, and alder (*Alnus*), with its distinctive bark and orange-pink wood, are together the predominant species. Birch, recognized by its characteristic silvery bark, is also widespread although subordinate. Support for this field assessment came from a microscopic examination of wood (trunk–roots) from

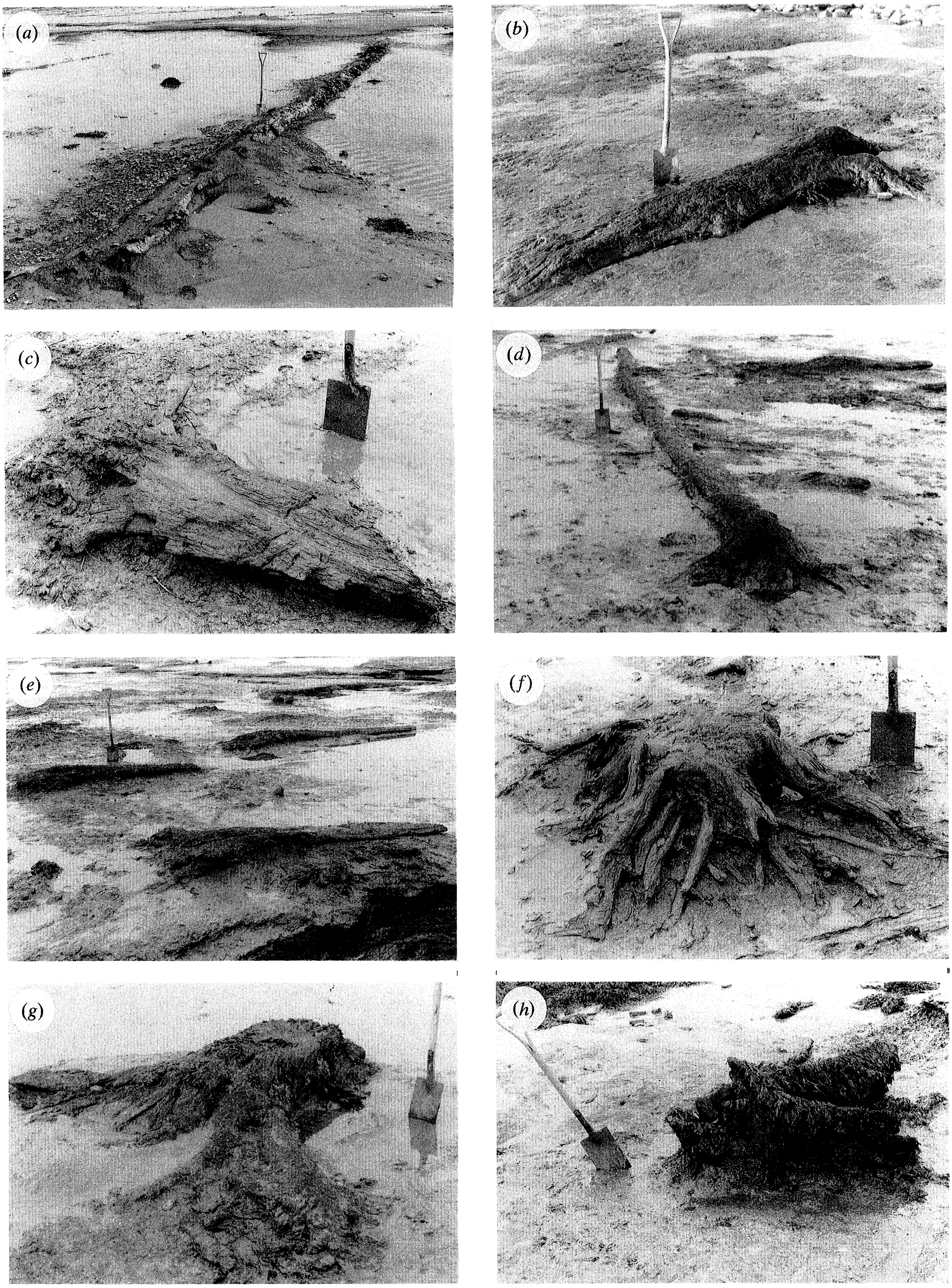

Figure 15. Wind-damaged trees of mid Flandrian age, Severn Estuary. Spade for scale 0.94 m long. (*a*) Windblown oak with rootball (bottom left), Hills Flats (locality 4). (*b*) Windblown alder with rootball (to right), Stolford (locality 13). (*c*) Windblown alder with rootball (to left), Grange Pill (locality 3). (*d*) Windblown alder with rootball (toward bottom), Gold Cliff (locality 9). (*e*) Group of subparallel windblown alder (rootballs to left) exposed on a peat ledge, Gold Cliff (locality 9). See also figure 16*b*. (*f*) Stump of oak with buttress-like, radiating roots, Grange Pill (locality 3). (*g*) Stump of alder, Gold Cliff (locality 9). (*h*) Stump of oak with buttress-like roots, showing windtilt (spade parallel with axis of trunk), Gold Cliff (locality 9). This specimen is exceptional in having a partly hollow trunk.

Table 2. *Distribution of tree taxa identified microscopically*

	number of examples			
locality	alder (*Alnus*)	birch (*Betula*)	oak (*Quercus*)	willow (*Salix*)
Grange Pill (loc. 3A, 3B)[a]	4	—	4	—
Hills Flats (loc. 4)	—	—	7	2
Oldbury Flats (loc. 5)	—	1	3	—
Gold Cliff (loc. 9)	5	2	2	—

[a] See figure 14*b* and table 3.

30 trees randomly sampled over four localities (table 2 and figure 14*b*), generously made by Dr I. B. K. Richardson and Dr R. Gray (Richardson's Botanical Investigations, Reading). Oak occurs at all the localities and alder and birch each at two. Willow (*Salix*) was recognised only at Grange Pill, where the post-glacial deposits partly infill a stream valley. The trees characteristic of the fen carr peats seem to be chiefly alder and birch.

The distinctive features of the trees from the woodland peats are their tall, slender and comparatively unbranched forms, pointing to growth in dense stands, and the scarcity of long-lived specimens, indicating frequent natural turnover. The oaks in a group mapped from a peat ledge at Hills Flats (figure 14*b*, locality 4) have slender, almost straight trunks with a few or no visible branches (figure 16*a*). The diameter at the top of the flare or widest part of the exposed stem varies between 0.32 and 0.56 m, and one trunk is at least 21 m long beneath the crown. Growth rings were not counted but, applying the woodman's rule of 25 mm of girth for each year of life, an age when toppled of the order of 50 years may be suggested. Similar features typify a representative group of alder with some birch (figure 16*b*) seen east of Gold Cliff (figure 14*b*, locality 9). The longest exposed trunk measured 9 m and the trees are mostly between 0.20 and 0.45 m in diameter, suggesting ages at death of the order of a few decades. A number of trees at Gold Cliff consist of two or three, approximately equal trunks which spring virtually at ground level from one rootball (one appears in figure 16*b*), as if the sapling had been damaged (?wind, deer cropping, human coppicing).

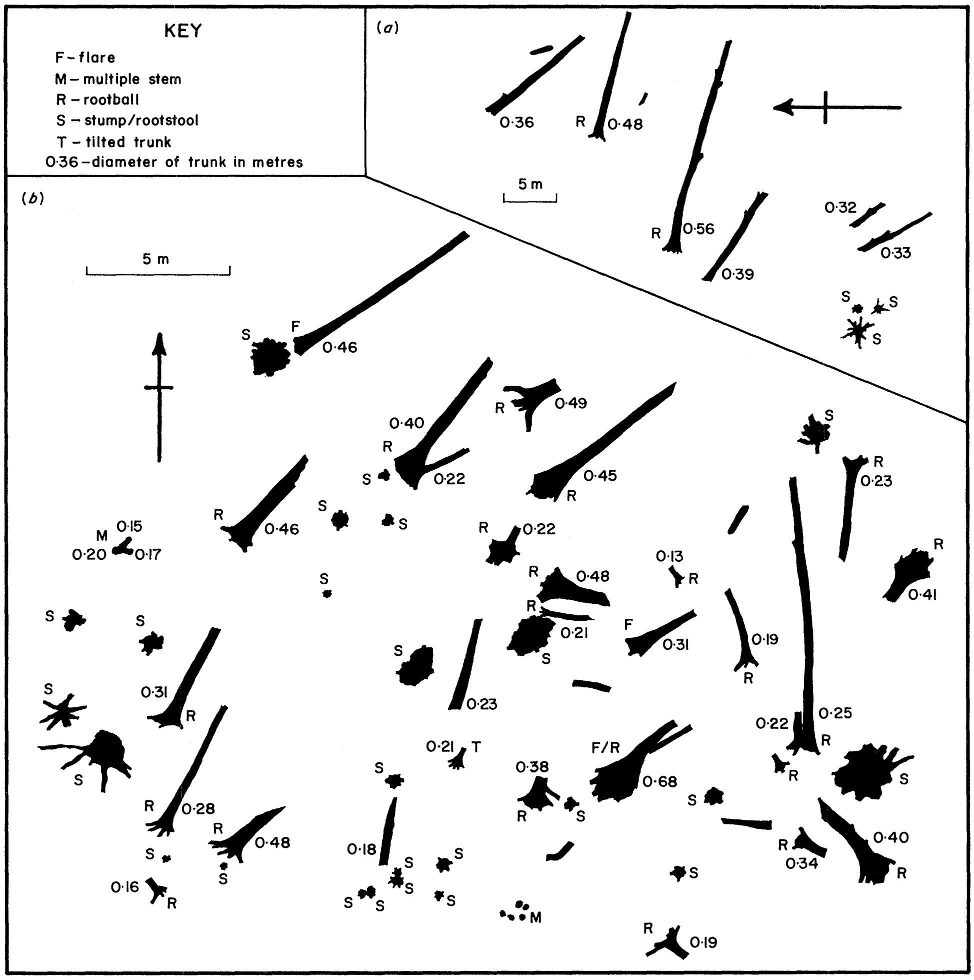

Figure 16. Examples of the distribution of mid Flandrian trees on intertidal peat ledges. (*a*) Hills Flats (locality 4). (*b*) Gold Cliff (locality 9) east of the bedrock island.

(*c*) *Inner estuary*

The inner Severn Estuary ranges downstream from the tidal limit to the last of the great bends at Awre (figure 14*b*). Peats at about Ordnance Datum with timber emerge at low tide at Longney Crib (SO 762128), Arlingham (SO 728114), Westbury-on-Severn (SO 713133) and Newnham (SO 697093), but the available exposures are insufficient for sampling fall-directions. Prevost *et al.* (1901) recorded alder, birch, cherry and oak from Westbury-on-Severn.

(*d*) *Middle estuary*

Peats at about Ordnance Datum are exposed intertidally at many localities in the middle estuary (table 3), down to the Aust-Chepstow narrows.

The extensive outcrop of Awre (SO 701069) invariably is heavily mud-obscured and, although hinting at many trees, gave no reliable fall-directions. The small intertidal outcrop of peats and silts at Sharpness (SO 667024) extends inland to the newer docks, where Lucy (1877) records alder, hazel (*Corylus*) and oak. The post-glacial sediments are well exposed at Berkeley Power Station (table 3, locality 1), where trees occur in an organic-rich paleosol and two higher peats. Of the peat-bearing outcrops at Severn House Farm (ST 643983, 637982), only the westerly one (table 3, locality 2) yielded trees. The substantial outcrop of interbedded silts and peats at Grange Pill revealed many trees, some in the lowest peat and the organic-rich paleosol from which it springs (table 3, locality 3A) and others in a higher bed (locality 3B). Mature rooted stumps sprawled across older, prostrate trunks were seen here, pointing to the comparative longevity of the woodland. The outcrops at Hills Flats (table 3, locality 4) and Oldbury Flats (table 3, locality 5) have much in common. The post-glacial sequence mantles a gently undulating bedrock surface (Allen & Fulford 1988). The succession begins with a sandy paleosol, locally organic-rich and grading to a basal peat, from which in the hollows of the bedrock surface spring included peats and organic-rich beds. Numerous trees are well exposed in the lowermost two peats and on top of the paleosol. Toward Oldbury Pill (ST 600935) the paleosol and weathered bedrock display an irregular microrelief recalling mound-and-pit, reviewed above. Trees are few to absent in the post-glacial deposits visible at Woolaston (ST 598983), Sedbury (ST 563942, 553926), and Littleton (ST 582910-576906).

(*e*) *Outer estuary*

The outer Severn Estuary extends as far downstream as a line drawn from Lavernock Point (Cardiff) to Weston-super-Mare (figure 14*b*). The post-glacial sequence is spectacularly exposed here.

On the shores of the Gwent Levels, a complex sequence of included peats and organic beds can be traced on broad ledges almost continuously from near Caldicot (ST 501870) to the Rumney River (ST 230774, 216757). The bedrock 'island' of Gold Cliff, where an organic-rich paleosol in sandy deposits and head grades into a basal peat, is pivotal to its character. Near Gold Cliff (table 3, locality 9) the main peat is approximately 1 m thick and abounds in substantial trees (figure 16*b*), as noted by Locke (1971) and by Smith & Morgan (1989). The forest here lasted for a number of generations, to judge from the mature, rooted stumps grown across already prostrate stems. In support of this inference, Smith & Morgan (1989) give the woodland phase at Gold Cliff a duration of almost 600 years, starting at about 5700 conventional radiocarbon years BP. Northeastward along the coast the woodland peats become thin and patchy and the trees smaller and more sparse (table 3, localities 8A, 8B and 6), although there are local increases in density (e.g. locality 7). The peat in harmony tends to divide into two or three leaves. The main peat is less well exposed southwest of Gold Cliff (table 3, localities 10 and 11), but similar trends are observed. The character of the peats at Nash and Rumney Great Wharf, as at Redwick, Magor and Rogiet, points mainly to fen carr and reed-sedge swamp.

The only tree-bearing peats exposed on the southern shores of the outer estuary occur in a lengthy outcrop at Wick St. Lawrence (table 3, locality 12). The trunks are small and sparse, suggesting a fen carr.

(*f*) *Inner Bristol Channel*

Few exposures of post-glacial estuarine silts and peats occur on the margins of the largely rock-bound Bristol Channel (figure 14*b*). Those at Barry (ST 1267), destroyed during dock construction, revealed oak, willow and conifers (Strahan 1896). The complex sequence at Stolford, of which Kidson & Heyworth (1976) give an account, crops out over extensive ledges and covers an undulating bedrock surface (table 3). Only one peat is exposed east of a large bedrock emminence (locality 13A). To the west, both a lower (locality 13B) and an upper (locality 13C) woodland peat appear. The forests seem to have been long-lived, as numerous examples were encountered of mature trees which had sprouted over the trunk of a predecessor. Woodland and fen carr peats with measurable trees appear widely among the patchy sands and gravels at Minehead (table 3, locality 14). Godwin-Austen (1865) described a peat with alder and oak from Porlock (SS 879481–870479), but little is now visible.

6. DIRECTION OF FALL OF MID FLANDRIAN TREES

(*a*) *Evidence of fall-direction and wind damage*

All of the criteria of fall-direction developed from my studies in contemporary woodlands affected by strong winds were applicable to the sub-fossil trees of the Severn Estuary and inner Bristol Channel (table 4).

The position of the rootball on the trunk was the criterion most readily applied. The sense of taper also proved useful, although some digging out of the trunk was often necessary before reliable measurements

Table 3. *Summary of sub-fossil wind-felled trees from the inner Bristol Channel and Severn Estuary*

			all trees						trees with rootball					
locality	name	British National Grid Reference	n	θ_m (deg)	R	σ_θ (deg)	κ	p	n	θ_m (deg)	R	σ_θ (deg)	κ	p
1	Berkeley Power Station	ST 650988–655993	11	113°	0.307	88.1°	0.64	>0.3	3	132°	0.254	68.3°	0.53	?
2	Severn House Farm	ST 637982	5	101°	0.624	55.6°	1.62	$>10^{-1}$	1	044°	—	—	—	—
3A	Grange Pill (lower peat)	ST 593981–590979	22	064°	0.705	47.9°	2.04	$<10^{-4}$	5	055°	0.896	26.8°	5.13	$<10^{-2}$
3B	Grange Pill (higher peat)	ST 593981–590979	21	079°	0.571	60.7°	1.40	$<10^{-2}$	13	073°	0.532	64.4°	1.30	$<10^{-2}$
4	Hills Flats	ST 621972–630978	29	110°	0.575	60.3°	1.42	$<10^{-3}$	6	143°	0.438	73.7°	0.98	$>10^{-1}$
5	Oldbury Flats	ST 599932–601937	26	075°	0.429	74.5°	0.95	$<10^{-5}$	5	198°	0.0671	133°	0.12	$>10^{-1}$
6	Rogiet	ST 453856–460858	15	063°	0.635	54.6	1.67	$<10^{-2}$	3	113°	0.658	52.4°	1.78	?
7	Magor	ST 439845–453856	56	074°	0.572	60.6°	1.41	$<10^{-5}$	28	062°	0.530	64.6°	1.26	$<10^{-3}$
8A	Redwick (northeast)	ST 419833–426836	11	079°	0.567	61.1°	1.39	<0.025	2	208°	—	—	—	—
8B	Redwick (southwest)	ST 405828	7	052°	0.768	41.6°	2.53	<0.025	2	181°	—	—	—	—
9	Gold Cliff	ST 368820–382821	47	070°	0.477	69.7°	1.09	$<10^{-3}$	33	058°	0.511	66.4°	1.22	$<10^{-3}$
10	Nash	ST 342822–355822	11	075°	0.566	61.1°	1.39	<0.025	3	075°	0.203	99.0°	0.41	?
11	Rumney Great Wharf	ST 233774–250784	27	088°	0.444	73.0°	0.99	<0.02	11	104°	0.576	60.2°	1.43	<0.025
12	Wick St. Lawrence	ST 351667–371674	7	056°	0.840	29.2°	3.48	$<10^{-2}$	1	122°	—	—	—	—
13A	Stolford (east)	*ca.* ST 235462	20	074°	0.512	66.3°	1.20	$<10^{-2}$	9	057°	0.430	74.4°	0.95	$>10^{-1}$
13B	Stolford (lower peat)	ST 217465–228462	40	075°	0.424	75.0°	0.94	$<10^{-3}$	9	173°	0.103	122	0.21	$>10^{-1}$
13C	Stolford (higher peat)	ST 217465–228462	122	093°	0.541	63.5°	1.30	$<10^{-10}$	105	096°	0.566	61.2°	1.38	$<10^{-10}$
14	Minehead	ST 973468–980468	32	087°	0.601	57.9°	1.52	$<10^{-5}$	24	087°	0.664	51.8°	1.84	$<10^{-4}$

Table 4. *Field criteria of fall-direction applicable to sub-fossil trees in the inner Bristol Channel and Severn Estuary*

criterion	number of applications
location of rootball	263
taper of trunk	192
branching direction	146
direction of tilt of trunk	12
location of broken end of trunk, matching stump and trunk	5
total applications	618
total trees	509
applications per tree	1.21

could be made. In most cases, however, taper could not be established, either because of limited preservation or because the long, slender trunk was effectively parallel-sided. The branching angle was readily established, either from protruding branches or internal knots (figure 17). Locally, the direction of tilt of a stump was exploited (figures 15*g* and 16*b*). Only where large numbers of trees were visible, as at Gold Cliff (locality 9) and Stolford (locality 13), were trunks found which could be oriented by either the position of the broken end or close proximity to, and alignment with, a stump of the same diameter and species (e.g. figure 16*b*).

What suggests that the trees were largely if not wholly wind-felled? Five lines of positive evidence present themselves. The high proportion of sampled trees with visible, well preserved rootballs (51.6%) points to windthrow, given their occurence chiefly in peats, and the finding from modern woodlands that windthrow predominates in natural moist forests and forested swamps (§ 3*b*). Judged by size (e.g. figure 16), the trees in the Severn Estuary and Bristol Channel at death were mainly youthful to early mature rather than in late maturity or old age. This feature is also compatible with wind damage as observed in modern forests (§ 3*b*). A closely related property of the sub-fossil trees indicative of wind-felling is the quality of the woody tissue, which suggests that they were mainly in perfect health at the time of fall. The exposed interiors of trunks invariably revealed wood of a uniform colour, consistency and hand-lens appearance, and very few stumps, rootballs and flares hollowed by decay, and consequently detritus- or sediment-filled, were detected; the vast majority of contemporary wind-felled trees were healthy at the time of fall. The fourth indication of wind-felling is the widespread occurence of groups of closely spaced and similarly oriented trees, suggesting series of swathes created by a number of wind events. Two sets of orientations are evident at Hills Flats (figure 16*a*);

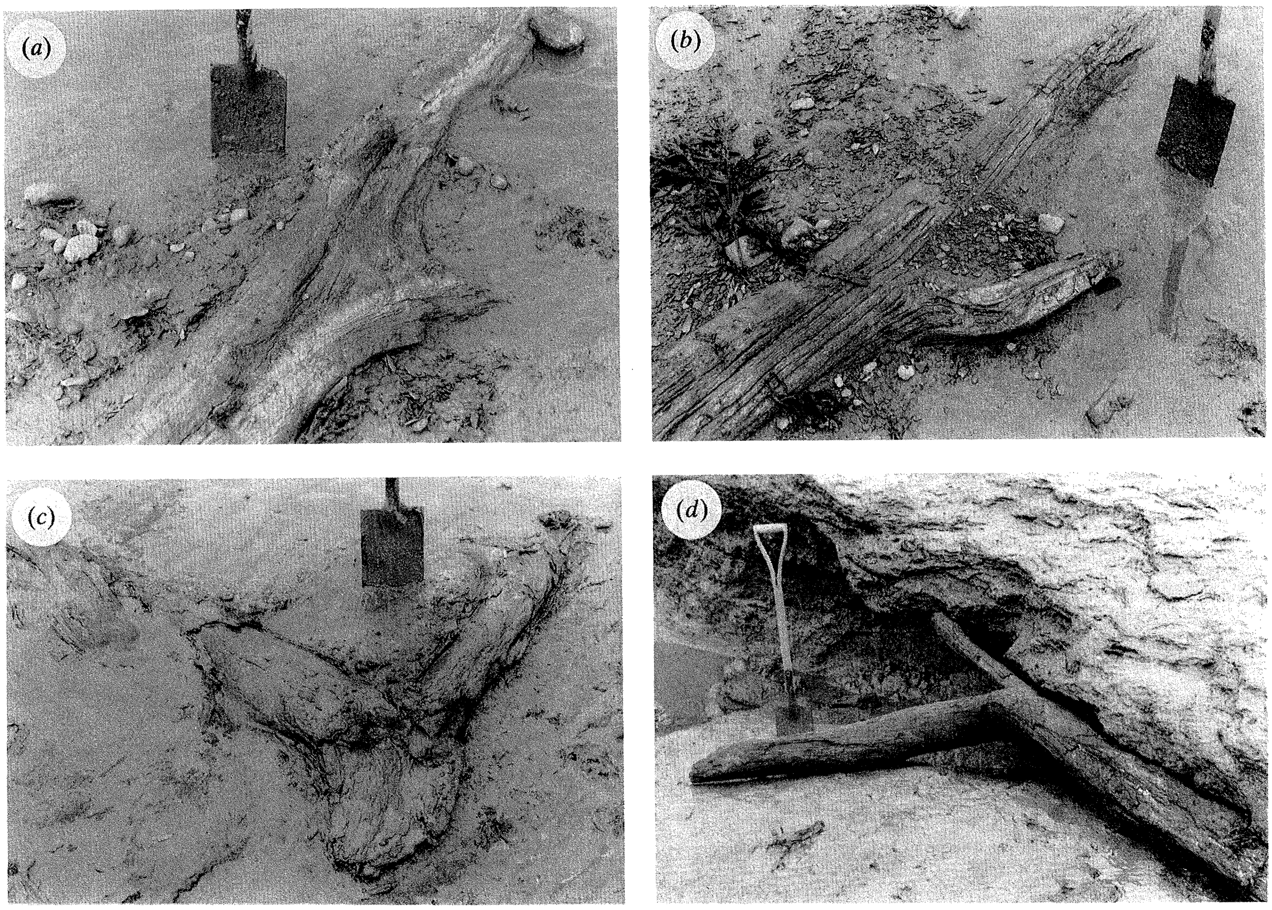

Figure 17. Wind-damaged trees of mid Flandrian age, Severn Estuary. Blade of spade for scale measures 0.14 m across. (*a*) Oak showing branching, Hills Flats (locality 4). (*b*) Oak showing branching, Hills Flats (locality 4). (*c*) Alder showing branching, Grange Pill (locality 3). Alder showing branching, Gold Cliff (locality 9).

at Gold Cliff (figures 15*e* and 16*b*) at least three preferred fall-directions emerge. Groups of close, near-parallel trees were also seen at Grange Pill (figure 14*b*, locality 3), Oldbury Flats (locality 5), Stolford (locality 13) and Minehead (locality 14). Finally, the relative coherence of the measured fall-directions, and their evident independence of the orientations of the shoreline, point strongly to felling by the wind (see figure 18 and below).

It is most unlikely that the trees were overturned and orientated by either tidal streams or river floods (e.g. McKnight *et al.* 1990; Hunt 1991) or by volcanic phenomena (e.g. Froggatt *et al.* 1981; Kieffer 1981; Foxworthy & Hill 1982; Fritz & Harrison 1985), because: (i) the trunks occur in the context of rooted peats; (ii) the peats lack included layers of coarse-grade or volcanic debris; and (iii) there is no known volcanic activity of late Quaternary date in southwest Britain. The area of the Severn Estuary is of very low seismicity, and the felling of the trees after death due to catastrophic flooding (see Atwater & Yamaguchi 1991; Atwater *et al.* 1991) can be safely excluded.

(*b*) *Data collection and analysis*

The localities numbered in figure 14*b* gave the data summarized in table 3. At all but four sites, the fall-direction of every exposed tree that could be orientated was measured. The trees plentifully exposed at Magor, Gold Cliff, Stolford and Minehead, however, were sampled by line-walking, in order to reduce the numbers of measurements. Two peat beds up to 1 m apart stratigraphically were sampled at each of Grange Pill (localities 3A, 3B) and Stolford (localities 13B, 13C). Listed in table 3 are values (Mardia 1972) for the vector mean fall-direction, fractional mean resultant vector, angular standard deviation, and von Mises concentration parameter. The calculations were made, firstly, on the ungrouped fall-directions, regardless of the criterion of orientation (overall $n = 509$), and, secondly, on the ungrouped directions established by rootball (overall $n = 263$), considered in principle to be the only wholly reliable criterion of fall-direction. Sites yielding small samples ($n \leqslant 10$) are portrayed as ray diagrams, whereas large samples ($n > 10$) appear in spoke form (see figures 18 and 19). The Rayleigh test (Curray 1956) was applied to each sample.

(*c*) *Local fall-directions*

Ray and spoke diagrams for individual localities (all criteria) appear in figure 18 (see also table 3). The distributions of fall-directions are mainly flat-topped

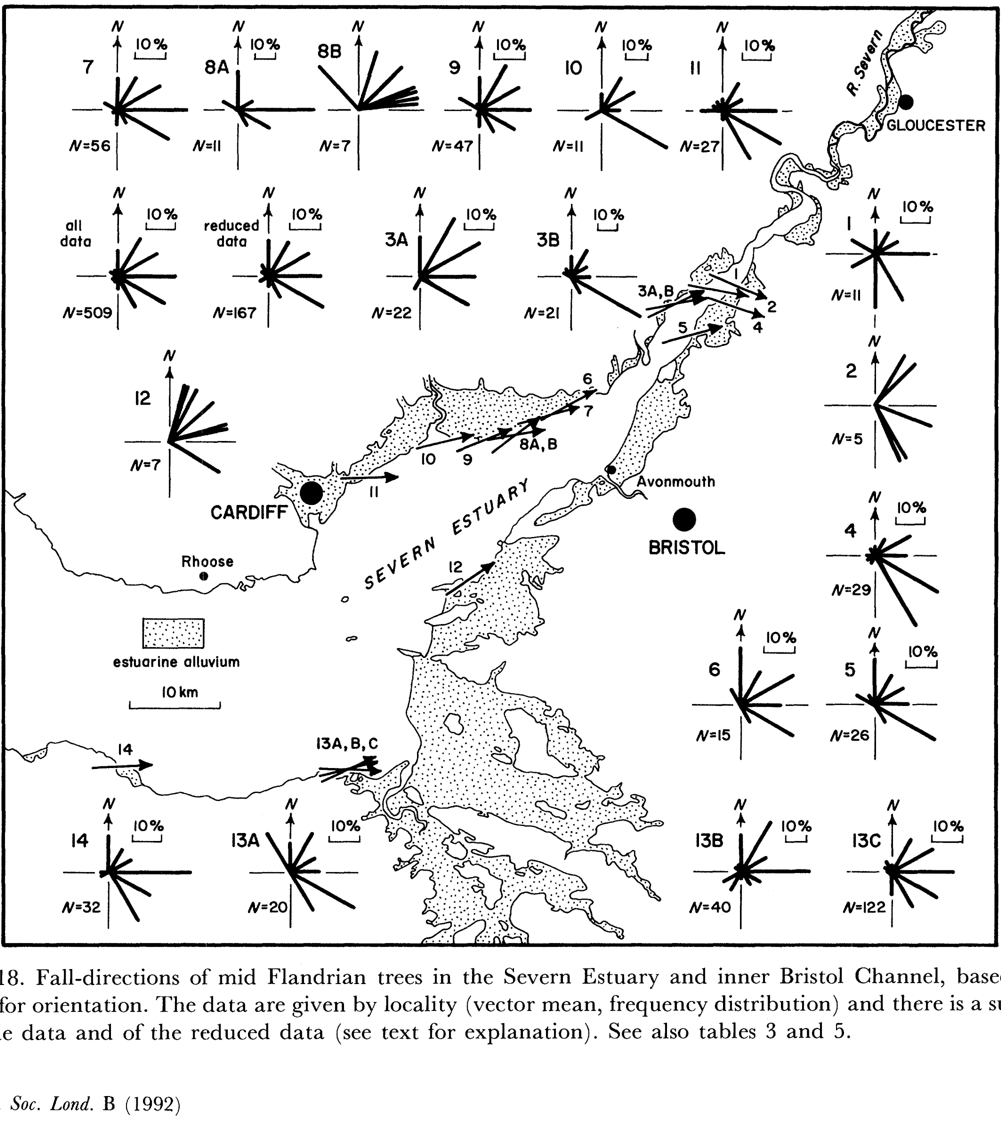

Figure 18. Fall-directions of mid Flandrian trees in the Severn Estuary and inner Bristol Channel, based on all criteria for orientation. The data are given by locality (vector mean, frequency distribution) and there is a summary of all the data and of the reduced data (see text for explanation). See also tables 3 and 5.

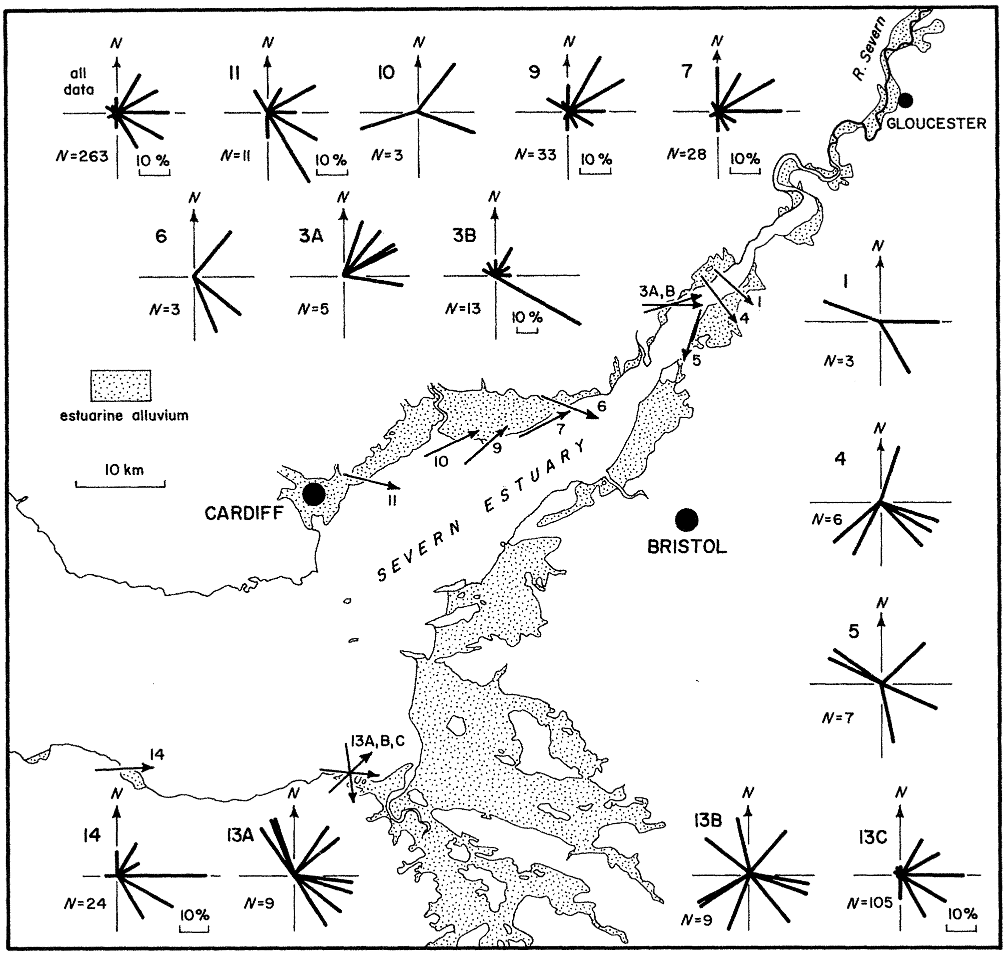

Figure 19. Fall-directions of mid Flandrian trees in the Severn Estuary and inner Bristol Channel, based on the position of the rootball. The data are given by locality (vector mean, frequency distribution) and there is a summary of all the data. See also tables 3 and 5.

(e.g. localities 3A, 7, 9 and 11) to weakly bimodal (localities 3B, 4, 5, 13A, 13B and 14), with a marked skew toward northerly points. Although several samples are too small to be statistically significant ($p \leqslant 5\%$), the vector mean fall-directions (051°–113°) all lie within an approximate 90° quadrant centred on due east. Only the middle estuary includes sites where the vector mean has a marked southerly component. The relationship in terms of absolute age between the two peats at each of Grange Pill (localities 3A and 3B) and Stolford (localities 13B and 13C) is unknown, but it is perhaps no coincidence that the younger peat in each case yields the more easterly mean ($p = 25\%$).

A less satisfactory picture is obtained when only trunks with rootballs are considered (figure 19, table 3), the data being reduced by approximately one-half. Disregarding three localities with only one remaining measurement, and a fourth with only two trunks with rootballs, the vector mean fall-directions now range from 055° to 198°. There is no significant change, however, in the form of the distributions.

(*d*) *Effect of topography*

Some of the between-site variation in the vector mean fall-direction (all criteria) seems due to an effect associated with the generalized orientation of the bedrock slopes that overlook each alluvial outcrop. The convention we adopt in specifying the orientation of these slopes (figure 20*a*) is to measure the clockwise angle from true north to the generalized contours of the slope, keeping the high ground within the angle. Sites are classified as 'leeward' where the trees point away from the high ground and as 'windward' where the trunks indicate the bedrock; they are further classified according as they lie on the left or right bank of the Severn Estuary and inner Bristol Channel. Wick St. Lawrence (locality 12), however, is treated as a right-bank site, for the nearest bedrock slopes (Middle Hope) lie to its right looking downstream.

The weak negative correlation between the mean fall-direction and the orientation of local bedrock slopes (figure 20*b* and table 3), calculated by pooling the two sets of data after subtracting 180° from each slope orientation in the left-bank set, accounts for 22% of the variance ($r = -0.47$). These slopes have the effect of rotating the mean fall-direction toward the normal to the generalized contours. The explanation for this effect, however, is at present unknown.

(*e*) *Regional fall-direction*

The pooled data (all criteria) yield a general vector mean of 080° associated with large measures of

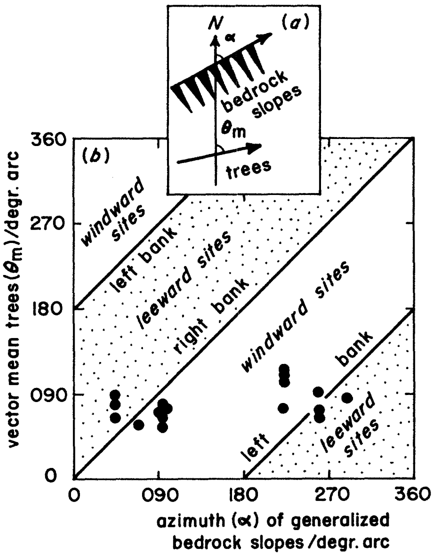

Figure 20. Influence of local topography on fall-directions of mid Flandrian trees in the Severn Estuary and inner Bristol Channel. See text for full explanation.

variance (figure 18 and table 5). As with many individual sites, the grand distribution is comparatively flat-topped and skewed toward northerly points. A similar distribution, but a slightly more easterly vector mean (084°), is obtained from only trees with rootballs (figure 19 and table 4). Both treatments may be criticized on the grounds that the sites are neither uniformly spread geographically (figure 14*b*) nor represented by a uniform number of measurements.

The ideally constrained sample for the estimation of the regional mean is one pooling uniform numbers of measurements drawn from sites uniformly spread geographically (e.g. Potter & Pettijohn 1977). With relatively so few sites, little can be done about their uneven spread, but there are two ways of minimizing bias from non-uniformity of sample size. The grand vector mean of the locality means is 079°, a slightly less easterly point than the two large pooled samples (figure 18 and table 5). Secondly, we may use random selection to reduce to an approximately uniform value the number of fall-directions representing each locality (5–10 observations per site was found attainable). Pooling these data (overall $n = 163$) gave as before a comparatively flat distribution of large variance skewed toward northerly points (figure 18 and table 5). The vector mean of 072° is slightly more northerly than the other grand means.

(*f*) *Directional range of tree-felling events*

The substantial spreads of fall-direction evident at individual localities and in the pooled samples (figures 18 and 19, tables 3 and 5) arguably record tree-felling events themselves of a certain range of direction. It is consequently natural to wonder to what extent the spread of event directions is narrower than some observed spread of fall-directions of individual trees. An approximate model answering this question can be created by identifying (i) a single, appropriate tree-felling event, and (ii) a probability density (likely to be theoretical) for tree-felling events affecting a region over a period.

As we wish without complicating matters unduly to gain an insight into individual localities, as well as the Severn Estuary-inner Bristol Channel as a whole, the appropriate tree-felling event is judged to be intermediate in variance between Windsor Great Park (west) and Chiltern Hills (table 1) and assumed to be von Mises in distribution ($\kappa = 3.2$). A wrapped normal distribution, however, is a more appropriate probabi-

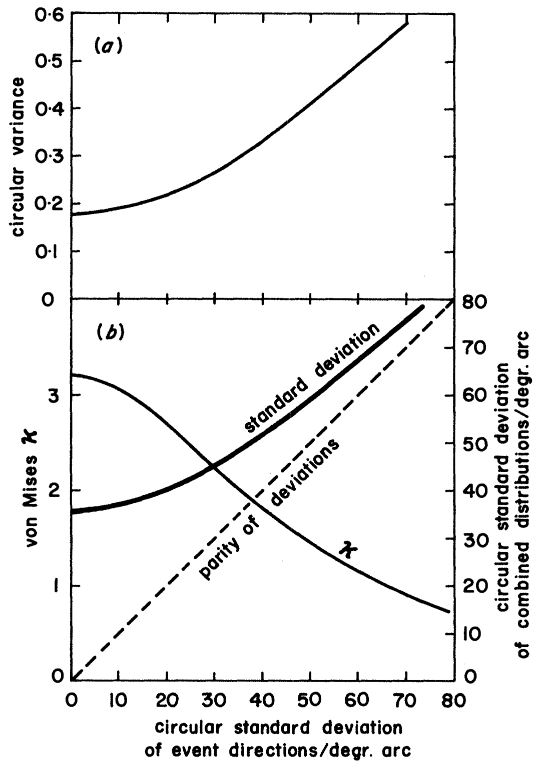

Figure 21. Properties of a semi-empirical model combining the variance of local tree fall-directions for a single strong-wind event with the variance of a population of events.

Table 5. *Statistical summary of fall-directions of sub-fossil trees in the inner Bristol Channel and Severn Estuary*

	n	θ_m (deg)	R	σ_θ (deg)	κ	p
pooled data (all criteria)	509	080°	0.523	65.3°	1.23	$< 10^{-20}$
pooled data (rootball only)	263	084°	0.473	70.1°	1.08	10^{-20}
locality vector means	18	079°	—	—	—	—
pooled reduced data (all criteria)	163	072°	0.537	63.9°	1.28	10^{-20}

lity density for event directions, given the flat-topped spoke diagrams (figures 18 and 19). Combining the two distributions, we obtain a new density which models the fall-directions of trees representing many events over a period in an area. Figure 21 shows how the calculated measures of variance for this distribution change with the angular standard deviation of event directions, the two standard deviations converging as the event directions become increasingly dispersed. Note that an event standard deviation of 0° corresponds to just one hypothetical wind-event of $\kappa = 3.2$.

This model leaves no doubt that the inner Bristol Channel and Severn Estuary were affected in mid Flandrian times by tree-felling events from a wide range of directions. Most sites yielding a large sample have a circular standard deviation of 60°–70°; the value for the pooled reduced data is 63.9° (tables 3 and 5). Entering figure 21 with these values, we find that the circular standard deviation of event directions is only about 10° smaller. Broadly, nine out of ten events appear to have been directed toward bearings from 345° (roughly N.N.W.) clockwise to 160° (roughly S.S.E.), with an emphasis on easterly points.

7. DISCUSSION

Drawing on the response of contemporary trees to strong winds, and noting the coastal setting in peat soils of the sub-fossil specimens, evidence is given above which strongly suggests that the fall-directions of the prostrate trees of the inner Bristol Channel and Severn Estuary were largely if not wholly determined by gale-force and stronger winds. The observed fall-directions (see figures 18 and 19, table 5) appear to define for the mid Flandrian epoch a regional pattern of strong winds which, although significantly dispersed, is dominated by blows toward easterly points (i.e. westerly winds, conventionally speaking). Does this inferred wind pattern compare with the contemporary strong-wind field and with winds predicted for the mid Flandrian?

Only a limited comparison is possible with the contemporary field, chiefly because the peats appear to record a number of woodland episodes, each of a decadal-century timescale, spread over many centuries, whereas instrumental records of wind in the area are restricted to the most recent decades. High-quality data are available only after 1970, from anemographs at Cardiff (Rhoose Airport)(ST 063679) and Avonmouth (ST 505787) (figure 18). The Cardiff instrument (74 m O.D.) lies on a plateau at about 60 m O.D. some 2 km north of equally tall sea cliffs and 15 km south of a bold (*ca.* 275 m) east-west escarpment. Much less influenced by local circumstances is the Avonmouth site (28 m O.D.), remote from hills on the outer edge of a wide coastal plain near sea level.

Figure 22*a–d* summarizes Meteorological Office data on the direction towards which the wind blows, speed (knots, Beaufort scale classes), and total hours at each speed for these sites over the periods 1970–79 and 1980–88. Important differences are seen between the sites, but at neither are strong winds common. Broadly, Avonmouth is the more exposed location, experiencing the highest frequency of strong winds. The direction toward which the wind blows is at each site bimodally distributed at low wind speeds. One mode is northerly to southeasterly; the other is approximately southwesterly. With increasing wind speed, the first mode at each station grows in dominance (see figure 22*e*). The dominant mode is more symmetrical at Cardiff than Avonmouth, however, and the subordinate mode at Cardiff is comparatively strong and persistent (see figure 22*a–d*, *f*, *g*). A marked northerly skew is a distinctive feature of the Avonmouth signature, especially at higher speeds (e.g. figure 22*g*). At neither site does the vector-mean direction vary much with speed (see figure 22*h*, table 6), but the overall mean at Avonmouth (064°), for near-gale and greater speeds, is 14° more northerly than at Cardiff.

Where sample size permits a fair comparison, only an Avonmouth-like signature (see figure 22*g*) is recognizable in the local distributions of tree fall-directions (see figure 18). The similarity is strongest at Magor (locality 7), Rumney Great Wharf (locality 11), and Minehead (locality 14), but the distributions at Oldbury Flats (locality 5), Gold Cliff (locality 9) and Stolford (locality 13C) seem also to be of the type. The northerly skew is even more exaggerated than at Avonmouth (see figures 18 and 22*g*), and the vector-mean fall-directions, although as expected less coherent, are more easterly by 6°–28° (see tables 3 and 6). Only the lowest peat at Stolford (locality 13B) reveals, in its southwesterly subordinate mode, any resemblance to the Cardiff signature (see figures 18 and 22*f*). The dominant mode, however, invites comparison only with Avonmouth.

Is the pattern of strong winds revealed here compatible with the wind field as modelled numerically for the mid Flandrian epoch? This epoch was a time of relative warmth in the area, as elsewhere in northwest Europe (e.g. Guiot *et al.* 1989), although an overall cooling trend is evident and there were brief eposides of rapid climate change (Barber & Coope 1987). Modelling has shown that southern Britain lay 6000 years ago beneath a vigorous westerly air stream (Kutzbach & Guetter 1986, COHMAP members 1988). Precisely that inference is enforced by the orientations of the sub-fossil trees in the Severn Estuary and inner Bristol Channel recorded above (see figure 18, tables 3 and 6). The tree fall-directions, however, are much more dispersed than the strong winds recorded over a 19-year period at Avonmouth, even when the additional variance associated with wind-felled trees is taken into account. This suggests that they record the passage of depressions on tracks of a wider range of directions than now (e.g. Thomas 1960, McCallum & Norris 1990), perhaps reflecting the rapid changes of climate that occured in the generally speaking relatively warm mid Flandrian epoch. If the dates of the trees can be better constrained, it may prove possible to add to the understanding of these episodes. There can now be little doubt that useful insights into the wind patterns of

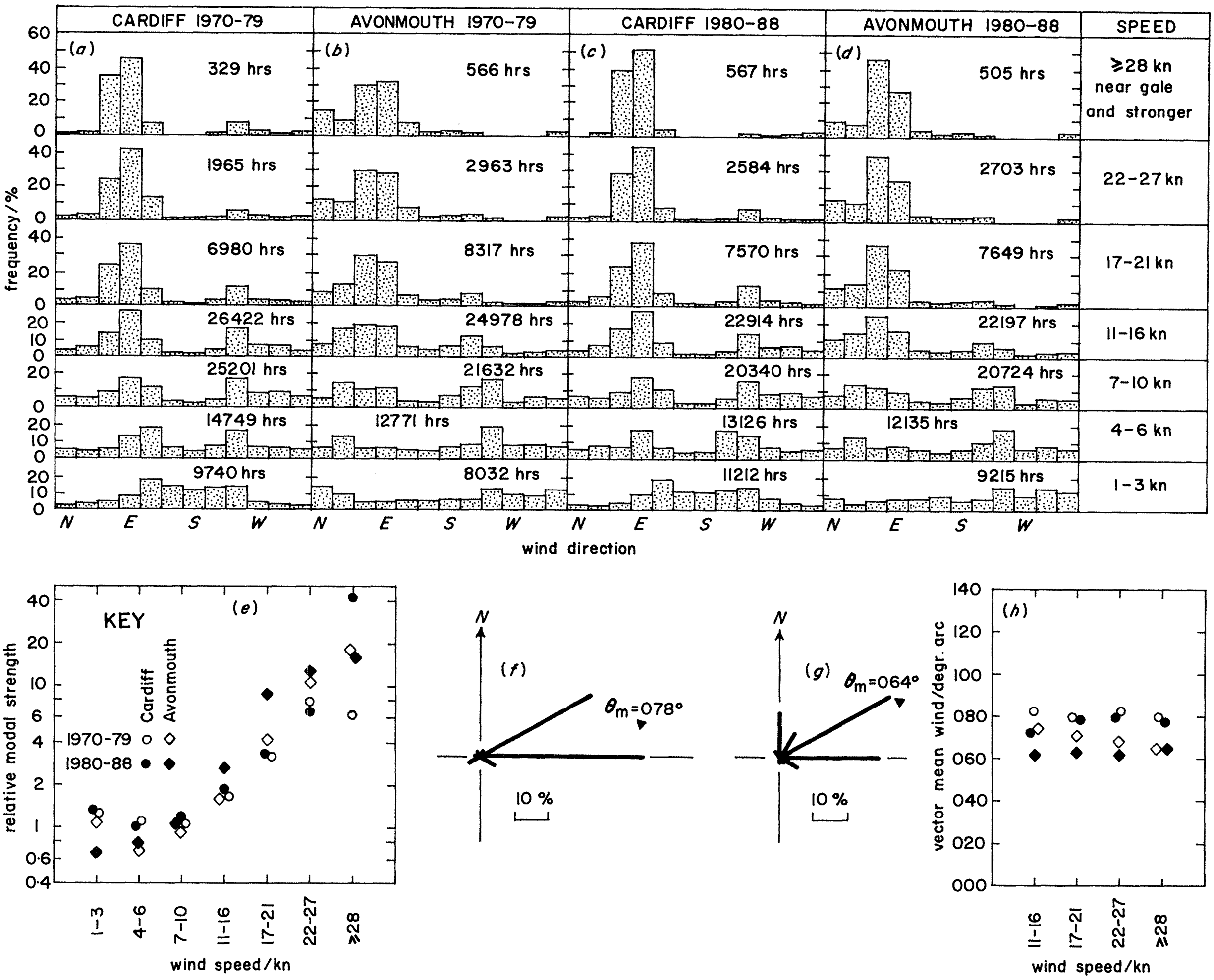

Figure 22. Wind climate at Cardiff (Rhoose Airport) and Avonmouth in 1970–79 and 1980–88. (*a–d*) Frequency distributions of direction toward which the wind blows as a function of wind speed. (*e*) Relative modal strength as a function of speed. (*f, g*) Frequency distribution of directions toward which the wind blows at respectively Cardiff and Avonmouth for speeds of 28 kn and greater. (*h*) Vector-mean wind as a function of speed (see *e* for key).

non-arid regions are obtainable from the orientations of fallen trees preserved in peats and related sediments. Future work should be directed toward widening these studies in the Flandrian and toward extending the methodology to older organic sediments, for example, the European brown coals of Tertiary age.

8. CONCLUSIONS

1. A literature review, combined with field studies on the effects in southeast Britain of the October 1987 and January 1990 storms, reveal that forest trees exhibit a well-defined response to strong winds (gale force and greater), which permits their fall-directions to be used as a trustworthy indicator of past wind fields.

2. Wind-felled trees are widely preserved in the estuarine peats (woodland and fen carr facies) of the mid Flandrian epoch exposed on the shores of the inner Bristol Channel and Severn Estuary in southwest Britain.

3. Local tree fall-directions measured from the field are strongly clustered and typically display an easterly mode marked by a strong skew toward northerly points.

4. The distributions of local fall-directions indicate as now a westerly circulation during the mid Flandrian epoch and the movement of the deeper depressions over a wide range of tracks.

Many people helped me in this study. My wife Jean generously assisted in the field, and I am most grateful to the Geologists' Association for a grant-in-aid from the Curry Fund. I am greatly indebted to Dr I. B. K. Richardson and Dr Rowena Gray of Richardson's Botanical Investigations for stimulating discussions in the field and for the identification of a selection of trunk and root tissues. Dr D. F. Cutler and Dr P. E. Gasson of the Royal Botanic Gardens, Kew, generously provided raw data on fall-directions from their Tree Root Survey following the October 1987 storm. I am grateful for help and advice received from officers of the Forestry Commission, especially Miss C. A. Oldham (Forest Research Station, Alice Holt), Dr C. P. Quine (Northern Research Station, Roslin), Mr S. Scott (Suffolk Forest District) and Mr L. M. Simpson (Thetford Forest District).

Dr Paul Valdes (Department of Meteorology) gave valuable advice. Helena Begg kindly undertook much of the statistical work. This paper is Reading University PRIS Contribution No. 239.

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Received 6 January 1992; accepted 17 August 1992

Figure 3. Mature silver birch involved in attached windsnap, Windsor Great Park (October 1987).

Figure 4. Mature silver birch involved in free windtilt, Windsor Great Park (October 1987).

Figure 5. Small windthrown beech, Windsor Great Park (October 1987). Note positions of rootball and crown, taper of trunk, and branching angle as criteria of fall-direction.

Figure 6. Rootballs attached to mature, windthrown beech trees, Windsor Great Park (October 1987). Note buttresses on the flare of each tree and the severed roots around the edges of the rootballs.

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Figure 7. Side view of the rootballs illustrated in figure 6, Windsor Great Park (October 1987). Note the plate-like character of the rootballs, the severed radial roots, and the scattered droppers.

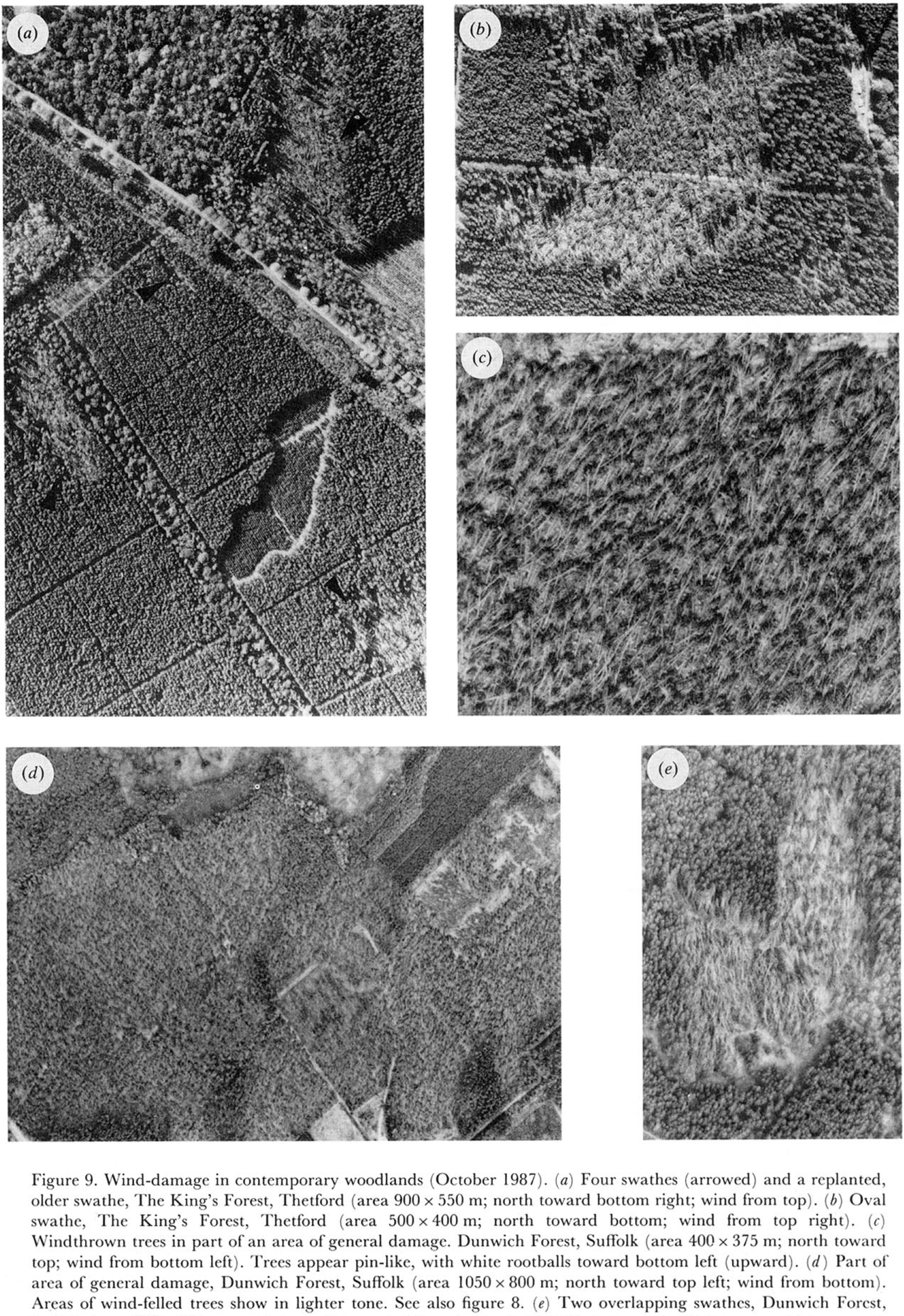

Figure 9. Wind-damage in contemporary woodlands (October 1987). (*a*) Four swathes (arrowed) and a replanted, older swathe, The King's Forest, Thetford (area 900 × 550 m; north toward bottom right; wind from top). (*b*) Oval swathe, The King's Forest, Thetford (area 500 × 400 m; north toward bottom; wind from top right). (*c*) Windthrown trees in part of an area of general damage. Dunwich Forest, Suffolk (area 400 × 375 m; north toward top; wind from bottom left). Trees appear pin-like, with white rootballs toward bottom left (upward). (*d*) Part of area of general damage, Dunwich Forest, Suffolk (area 1050 × 800 m; north toward top left; wind from bottom). Areas of wind-felled trees show in lighter tone. See also figure 8. (*e*) Two overlapping swathes, Dunwich Forest, Suffolk (area 250 × 200 m; north toward top; wind from bottom). MAFF photographs. Crown copyright reserved.

Figure 15. Wind-damaged trees of mid Flandrian age, Severn Estuary. Spade for scale 0.94 m long. (*a*) Windblown oak with rootball (bottom left), Hills Flats (locality 4). (*b*) Windblown alder with rootball (to right), Stolford (locality 13). (*c*) Windblown alder with rootball (to left), Grange Pill (locality 3). (*d*) Windblown alder with rootball (toward bottom), Gold Cliff (locality 9). (*e*) Group of subparallel windblown alder (rootballs to left) exposed on a peat ledge, Gold Cliff (locality 9). See also figure 16*b*. (*f*) Stump of oak with buttress-like, radiating roots, Grange Pill (locality 3). (*g*) Stump of alder, Gold Cliff (locality 9). (*h*) Stump of oak with buttress-like roots, showing windtilt (spade parallel with axis of trunk), Gold Cliff (locality 9). This specimen is exceptional in having a partly hollow trunk.

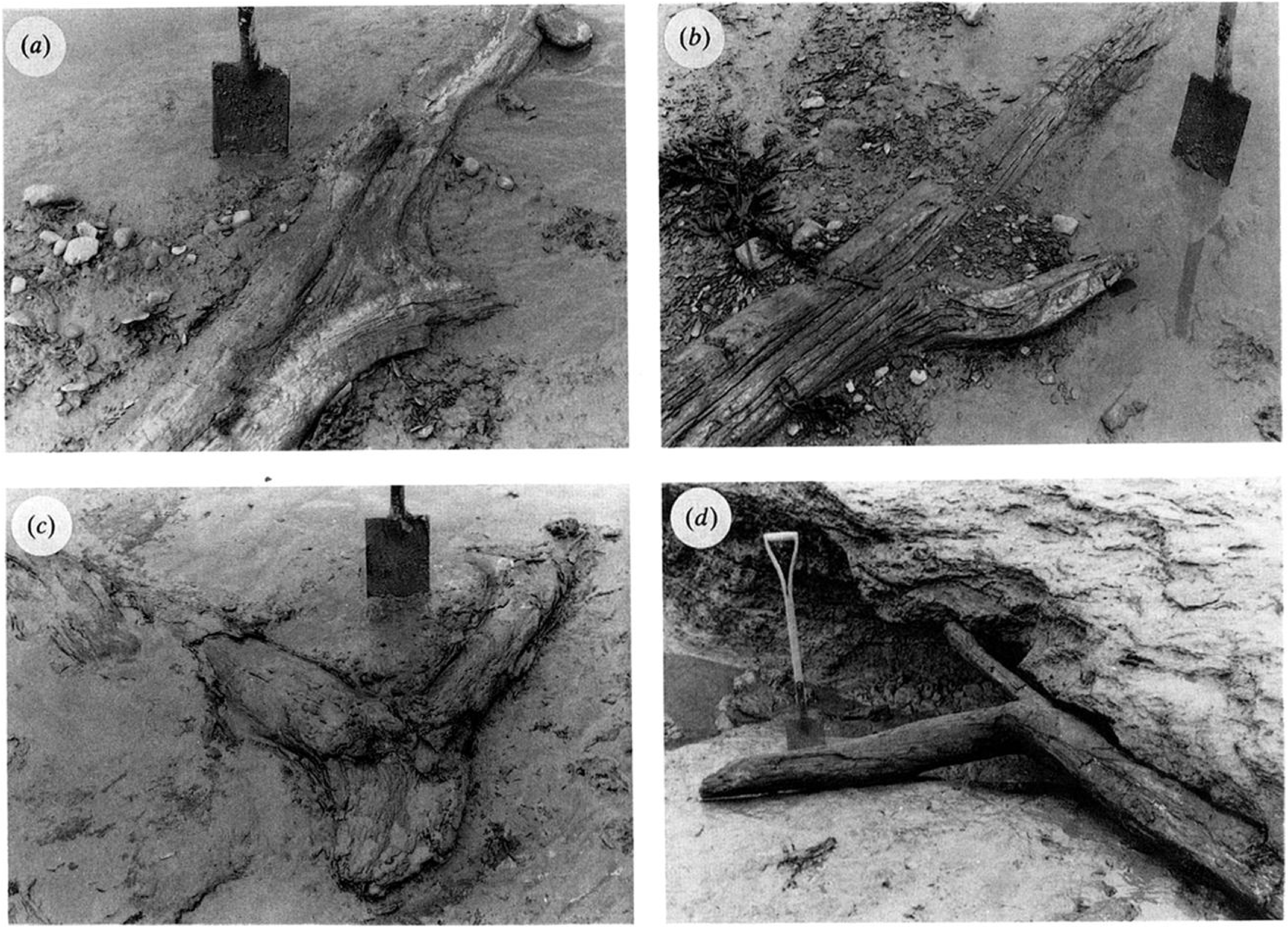

Figure 17. Wind-damaged trees of mid Flandrian age, Severn Estuary. Blade of spade for scale measures 0.14 m across. (*a*) Oak showing branching, Hills Flats (locality 4). (*b*) Oak showing branching, Hills Flats (locality 4). (*c*) Alder showing branching, Grange Pill (locality 3). Alder showing branching, Gold Cliff (locality 9).