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The wide range of climate in the Pacific Northwest of America, due to the proximity of the Pacific Ocean and variation in altitude, has caused the existence of several climax forest associations. In addition the Bunchgrass Prairie and Desert Shrub vegetational climaxes cover the dryer areas east of the Cascade Mountain Range. The great relief also permits the occurrence of numerous life zones in this region. The writer has made pollen studies of bogs located within several climax forest associations and life zones, from which were interpreted the postglacial forest succession and tentatively the climatic trends. This has been done with cognizance of the sources of error involved in pollen statistics and interpretations thereof. The bog of this study is located within the Spruce-Hemlock climax on the west side of the Olympic Peninsula, Washington. It is situated in T. 27 N., R. 13 W. in Jefferson County about six miles south of the village of Forks. It lies south of the Bogachiel River just west of the Olympic Highway, ten miles from the Pacific Ocean at an elevation of less than 500 feet above sea level. A strip along the northern and eastern sides of the Olympic Peninsula was glaciated by the Pleistocene continental glaciers, while the Olympic Mountains were subjected to local mountain glaciation. Between the mountains and the ocean is an unglaciated coastal plain from 10 to 20 miles wide and not over 400 feet in elevation except in local hilly districts. This plain is covered with glaciofluvial deposits from mountain glaciation, but due to postglacial uplift the larger streams have incised themselves and removed much of the Pleistocene deposits (Fenneman, 1931).

The peat and other pollen-bearing sediments have been deposited in a shallow depression in glaciofluvial deposits and consequently are of postglacial origin. A profile of the bog has been published by Rigg (1938). The central portion is covered with an ericad associes of Labrador tea *(Ledum groenlandicum)*, bog laurel *(Kalmia polifolia)*, and cranberry *(Vaccinium oxycoccus)*, and *Sphagnum* moss. Scattered on the bog with no zonation, grow sedge (*Carex* sp.), false hellebore *(Veratrum caudatum)*, hardhack *(Spiraea douglasii)*, wild lily-of-the-valley *(Mianthemum dilatatum)*, star flower *(Trientalis latifolia)*, *Polytrichum juniperinum*, and *Hypnum* sp. On the margin grow red alder *(Alnus oregona)*, salal *(Gaultheria shallon)*, skunk cabbage *(Lysichitum americanum)*, dogwood *(Cornus canadensis)*, bracken fern *(Pteridium aquilinum)*, and several species of willow (*Salix* spp.) Trees present in order

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of their apparent invasion are western white pine *(Pinus monticola)*, western hemlock *(Tsuga heterophylla)*, western red cedar *(Thuja plicata)*, Sitka spruce *(Picea sitchensis)*, and cascara *(Rhamnus purshiana)*. The bog has been drained by a series of ditches, and due to the lowering of the water table the surface vegetation is assuming a mesophytic character. The area comprises some 30 acres.

Peat samples were obtained with a Hiller sampler at decimeter intervals. The depth of the bog in the area of sampling near the center is 2.5 meters. It is underlain with a sandy silt which grades into clay at 2.4 meters. Brown sedimentary peat with some fiber is present from this level to 1.9 meters where it changes into a silty sedimentary peat. At 1.4 meters it consists of practically pure silt. This grades into a dark fibrous peat at 1.1 meters, and this in turn changes to brown fibrous at 0.8 meters which is present to the surface. The silty sediment was examined[1] for volcanic ash, but none was present. The ash, which occurs as a layer or as dispersed crystals in many bogs in the Pacific Northwest, is seemingly absent from the Olympic Peninsula (Rigg, 1938, Hansen, 1940a).

Forests in Adjacent Areas

The bog lies within the Humid Transition Life Zone (Piper, 1906). This life zone is forested chiefly with the Hemlock-Cedar climax in which the most abundant and characteristic tree is Douglas fir *(Pseudotsuga taxifolia)*. The latter is a subclimax species which has been able to persist because of extensive periodic fires which interrupted the normal succession toward the climax (Munger, 1940). Along the Pacific Ocean in the fog belt, however, there is a narrow strip in which Douglas fir plays little part in the forest succession. This is the Spruce-Hemlock climax (Jones, 1936). This forest extends from the ocean to an altitude of about 1000 feet and may be composed of a high percentage of Sitka spruce. Spruce is abundant along the immediate coast, but gradually thins out and becomes mixed with other species farther inland. The most important of these are western hemlock with some western cedar, Douglas fir, western white pine, lodgepole pine *(Pinus contorta)*, western yew *(Taxus brevifolia)*, lowland white fir *(Abies grandis)*, and silver fir *(A. amabilis)*. As the elevation increases to the east and the Transition gives way to the Canadian zone, western white pine, silver fir, and noble fir *(Abies nobilis)* become more abundant. Broadleaf trees of the Spruce-Hemlock climax growing chiefly on floodplains include red alder, large-leaf maple *(Acer macrophyllum)*, and black cottonwood *(Populus trichocarpa)*. Forest type maps (1936) indicate that six forest types exist within a ten mile radius to the bog. At least 75 per cent of this area is forested with spruce-hemlock types. Others in order of their area are western cedar, Douglar fir, balsam fir-mountain hemlock, and small zones of alder-maple along floodplains of the larger streams.

The Northwest Coast receives the heaviest annual precipitation in the United States. In his classification of the climates of North America, Thorn-

[1] Examined by Dr. H. A. Coombs, Dept. of Geology, Univ. of Wash., Seattle.

thwaite (1931) designates most of the Olympic Peninsula as having a wet, microthermal climate, with adequate precipitation at all seasons. The mean annual precipitation at Forks with an elevation of 375 feet is about 115 inches, and the mean annual temperature is 49 degrees. The prevailing winds throughout the year are from either the southwest or the northwest.

Methods

In preparation for study, slides were made with the usual potassium hydrate method (Hansen, 1940a). One-hundred and fifty pollen grains were identified from each level. The non-significant pollen was also recorded but not used in the computation of percentages (Table 1). Those significant species recording 1.5 per cent or less are listed in the table as 1 per cent. The procedure employed in identifying fossil pollen has been described in recent papers (Hansen, 1940b, 1941a, 1941b), and will not be discussed here in detail. Separation of specific pollen of *Pinus, Abies,* and *Picea* is based upon the size ranges of the cell, which were determined by measurements of modern pollen. Most species of each genus show a distinct gradation but with some degree of overlap. Fossil pollen falling within the limits of overlap of smaller or larger species is discarded as unknown and listed in the table as such. The size range of silver fir is within those of the smaller *Abies grandis* and larger *A. nobilis*. In this paper pollen within the size range of *A. grandis* is listed under this species, although some of it may well be that of *A. amabilis*. That listed as *A. nobilis* may likewise include some of the silver fir. The pollen of *Tsuga heterophylla* may be separated from that of *T. mertensiana* by the presence of bladders on the latter, although an occasional pollen of mountain hemlock may have minute or no bladders at all.

Forest Succession

It does not seem possible to estimate the proportion of postglacial time represented by the peat and other pollen-bearing sediments. The bog lies on glaciofluvial deposits and therefore must be of postglacial origin, although its shallow depth may denote a relatively short period of time. This is further suggested by the fact that a wet climate tends to foster a rapid rate of peat deposition. The absence of cattail, water lily, pondweed, and other hydrophytic plant pollen is significant in that it marks the absence of the hydrarch succession which usually takes place in standing water. Sphagnum moss grows abundantly on the damp forest floor in this area, and its occurrence in wet depressions may result in the development of thick layers. A subsequent influx of other bog plants such as Labrador tea, bog laurel, and cranberry may occur to form a bog associes. The absence of woody and Sphagnum peat in the lower levels of the bog of this study, as well as the occurrence of sedimentary peat and silt, tends to minimize the possibility of such a successional trend. The fact that two-thirds of the depth is composed of silt and sedimentary peat, indicates that it may represent much of postglacial time because such deposits are of slow accumulation. This is exemplified by a peat deposit in northern Washington which is only 3.25 meters deep, the lower half being composed

chiefly of sedimentary peat (Hansen, 1940b). The pollen profile indicates, however, that it records most of the postglacial forest succession in adjacent areas. The lack of a volcanic ash layer is unfortunate, because if present the recorded forest succession could be correlated chronologically with that of other bogs in the Pacific Northwest.

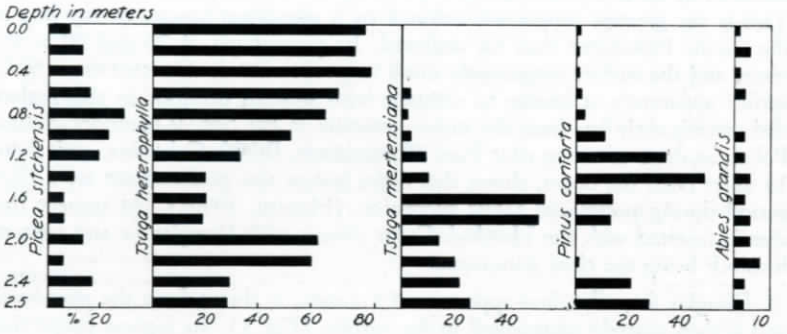

Fig. 1. Pollen profiles, Forks Bog.

The forests as recorded in the earliest pollen-bearing sediments were composed chiefly of lodgepole pine and western and mountain hemlock. The first two record 28 per cent each and the latter 26 per cent in the lowest level (Fig. 1). Other species represented at this level are western white pine, Sitka spruce, and lowland, silver, and noble fir. The low representation of lodgepole pine further suggests that some postglacial time had elapsed before the initial pollen-bearing sediments were deposited. Other bogs in the Pacific Northwest evidently recording most or all of the postglacial period show lodgepole pine as being the most abundant tree when the lower strata were laid down (Hansen, 1938, 1940a, 1941a). This seems to have been general east of the Cascade Range as well as in the Puget Sound region (Hansen, 1939a, 1939b, 1940b). At Glacier Bay, Alaska, however, lodgepole pine at present apparently has a very minor place in pioneer forest invasion of recently deglaciated valleys (Cooper, 1939). In this region Sitka spruce, western hemlock, and mountain hemlock constitute both the pioneer and climax forest. Likewise in southwestern Alaska, near Kodiak, Sitka spruce is the pioneer invader of areas that apparently were unforested during the latter part of the Pleistocene (Griggs, 1934). It is possible that the present climate in these regions of Alaska may be somewhat similar to that which existed when the lower pollen-bearing sediments of this study were deposited.

There are five significant trends in the profiles worthy of consideration. The first is the rapid initial increase in western hemlock to 62 per cent followed by its sharp decrease to 19 per cent in the succeeding level. Second, mountain hemlock increases precipitately from 14 per cent at 2 meters to 54 per cent at 1.6 meters, then decreasing to none in the upper three horizons. Third, this is followed by a sharp increase in lodgepole pine from none at 2 meters to 49

per cent at 1.4 meters. It likewise declines with a steep gradient to low proportions in the balance of the profile. Fourth, the profile of Sitka spruce somewhat parallels that of western hemlock, reaching its maximum of 29 per cent at 0.8 meters and then declining to the surface. Fifth, the maxima successively attained by western hemlock, mountain hemlock, and lodgepole pine are followed by an abrupt increase in western hemlock to 82 per cent at 0.4 meters. This is the greatest proportion attained by a significant species in any bog in the Pacific Northwest thus far analyzed. Its percentages of 76 and 80 at 0.2 meter and the surface respectively mark its predominance in recent time. Sitka spruce apparently is unable to compete with western hemlock in this region, and consequently has been the minor associate in the Spruce-Hemlock climax. Pollen analysis of a bog near New Westminster, British Columbia, and about 15 miles from the ocean, shows that Sitka spruce was predominant for a brief period during postglacial forest succession (Hansen, 1940a). At present this area is forested with the Hemlock-Cedar climax, with Douglas fir and western hemlock being the chief dominants.

Douglas fir pollen first appears at 1.4 meters, is absent from the next level, and is then sparsely represented to the surface (Fig. 1). Its highest proportion of 6 per cent at 1 meter indicates that it has not been as important in postglacial forest succession here, as in the Puget Sound region (Hansen, 1938, 1940a, 1941a). Lowland white and silver fir maintain a static record throughout, together reaching their highest percentage of 10 at 2.2 meters. Noble fir is best represented in the lower half of its profile. A slight increase in western white pine at the surface is probably due to its recent invasion of the bog. The presence of considerable silt from 1.8 to 1.1 meters is concurrent with the maxima attained by mountain hemlock and lodgepole pine. The silt may indicate increased erosion and flooding of the bog surface by nearby swollen streams. The sudden increase of mountain hemlock pollen at these levels may be a result of its transportation by flood waters from higher elevations to the east. The succeeding increase in lodgepole pine is suggestive of edaphic disturbance, perhaps brought about by these same floods. A similar influx of lodgepole pine concurrent with the deposition of silt and volcanic ash in a west central Oregon bog lends support to this hypothesis (Hansen, 1941b). The re-establishment of western hemlock and Sitka spruce may mark the modification of the edaphic conditions, as the former requires humus for germination and growth of its seedlings.

Broadleaf trees best represented are red alder and large-leaf maple. Alder records 376 pollen grains at the 1 meter level, which may reflect the change in conditions concurrent with the deposition of silt. A large number of composite pollen grains of a species of the Cichorieae tribe occurs in the silty levels, which may also be related to altered environmental conditions at this time (Table 1).

Climatic Considerations

It seems probable that postglacial forest succession in the Pacific Northwest, at least west of the Cascade Range, has been normal succession rather than a result of marked climatic changes. Normal succession is that which takes

TABLE 1.—Percentages of Fossil Pollen, Forks Bog.

Depth in meters	2.5	2.4	2.2	2.0	1.8	1.6	1.4	1.2	1.0	0.8	0.6	0.4	0.2	0.0
Pinus contorta	28	21	1	..	13	14	49	34	11	3	2	1	1	1
P. monticola	7	4	1	1	1	..	2	1	1	..	2	1	2	6
Pseudotsuga taxifolia	..	..	..	..	..	..	2	..	6	1	2	1	1	3
Tsuga heterophylla	28	29	60	62	19	20	20	33	52	65	70	82	76	80
T. mertensiana	26	22	20	14	52	54	10	9	3	2	3	..	..	..
Picea sitchensis	6	17	6	13	6	6	10	19	23	29	16	13	13	8
*Abies nobilis***	1	3	2	4	2	1	1	..	..	..	1	..	1	..
*A. grandis****	4	4	10	6	6	4	6	4	4	..	4	2	6	2
A. lasiocarpa	..	..	..	..	1	1	..	..	..	..	..	..	..	..
Pinus spp.**	16	17	3	3	5	3	14	17	7	4	3	1	..	3
Abies spp.**	5	4	3	1	2	4	2	3	1	1	2	..	..	..
*Gramineae**	..	..	1	2	8	5	1	..	1	..	2	1	..	..
*Compositae**	3	1	19	6	48	60	40	5	8	1	..	..	1	1
*Alnus**	..	..	1	1	3	..	1	10	376	26	32	8	19	5
*Acer**	1	1	4	1	10	4	5	1	3	2	2	..	1	1
*Salix**	1	..	3	..	2	1	..	1	..	1	3	1	..	..
*Fraxinus**	..	..	..	..	..	..	..	..	..	..	3	1	..	..
*Ericaceae**	..	..	1	..	5	6	3	4	7	9	15	37	72	22
*Cyperaceae**	18	4	6	16	72	11	6	2	2	12	9	22	15	2

***May include pollen of *Abies amabilis*.

**Number of Pinus and Abies pollen discarded as unknown and not computed in percentages.

*Number and not computed in the percentages.

place under more or less static climate through competition of the species present, and as a result of their modification of the environment. To be sure, the reaction of the plant upon the environment may in itself bring about alteration of the climate. A species may not respond to a change in a given environmental factor unless it is a limiting one and at a critical minimum or optimum. If at or above the optimum, an increase in the degree of that factor is not likely to be reflected in positive response by the plant. This probably has been true concerning precipitation on the Northwest Coast during postglacial time. A substantial increase or decrease would have little direct effect upon forest succession. Indirectly it may influence succession by alteration of the edaphic and physiographic conditions, as is suggested by the lodgepole pine maximum at 1.4 meters. As mentioned in a previous paper, the question arises as to what magnitude of fluctuation in the pollen profile of a species is essential in order to denote a change in forest composition, and to what degree does a change in forest composition justify an interpreted climatic trend.

If any climatic trends are depicted in the profiles of this study, it would seem to concern temperature rather than moisture. An initial cool climate is suggested by the presence of western white pine and mountain hemlock in the lowest level, as well as by the recent glacial epoch. A gradual warming to a maximum followed as is suggested by the increase in western hemlock. The successive increases in mountain hemlock and lodgepole pine may be indicative of increased precipitation reflected in edaphic changes, but not temperature changes. The increase in the former does not necessarily denote a correspond-

ing decrease in western hemlock, but merely reduces the relative proportions of western hemlock pollen in the peat. It is probable that a gradual increase to a maximum would have been recorded by the latter if it were not for the over-representation of mountain hemlock and possibly lodgepole pine.

Summary

Pollen analysis of a post-Vashon peat deposit in the Spruce-Hemlock forest climax on the west side of the Olympic Peninsula denotes the predominance of western hemlock with some Sitka spruce during much of the time represented, which may or may not constitute most of postglacial time.

Three peaks are attained successively upward in the pollen profiles of western hemlock, mountain hemlock, and lodgepole pine. The maximum of mountain hemlock may have been due to the transportation of its pollen from higher altitudes in the Olympic Mountains to the east. If this is true it would not reflect a climatic fluctuation. The presence of silt with little organic matter at the level of lodgepole pine maximum suggests edaphic changes. Douglas fir is sparsely represented and was never important in postglacial forest succession in this region. This is consistent with its minor status in the present forest complex.

Climatic trends are not clearly evidenced, and if such occurred, temperature rather than moisture was apparently the controlling factor.

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