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THE PYGMY FOREST-PODSOL ECOSYSTEM AND ITS DUNE ASSOCIATES OF THE MENDOCINO COAST

H. JENNY, R. J. ARKLEY, and A. M. SCHULTZ

INTRODUCTION

Along the Mendocino coast some twenty irregular patches of pygmy forest, dominated by stunted cane-like cypresses (*Cupressus pygmaea*) and dwarfed bishop (*Pinus muricata*) and Bolander pines (*Pinus contorta* ssp. *bolanderi*), are surrounded by belts of tall bishop pines and shore pines (*Pinus contorta*) and by luxurious regional forests containing giant redwoods (*Sequoia sempervirens*) and Douglas firs (*Pseudotsuga menziesii*). This striking forest differentiation, marked by floristic endemism, has fascinated botanists ever since Bolander's early explorations over a century ago.

Bishop and Bolander pines, but not the shore pine, are closed-cone pines. Mason (1934) approached the problem of the origin of the coastal closed-cone pine forests from a broad point of view. Looking for natural barriers that would conserve pines, he ruled out—correctly we think—local climates, topographic constellations and especially country rock, as there are no serpentines, quartzites or other rock extremes. Mason then searched for a water barrier and assumed, in analogy with the fossil and living forests on Santa Cruz I. off Santa Barbara, that the coastal strips used to be Tertiary pine-populated islands that later united with the mainland and preserved their unique flora against infiltration from the continental forest. Just how the aggressive invaders from the regional redwood and Douglas fir forest were kept at bay during hundreds of thousands of years could not be explained. A good account of Mason's ideas is given by Cain (1944) and more recently by Langenheim and Durham (1963).

The possible role of soils in the floral discontinuities of the greater Fort Bragg area came into focus with the work of the Mendocino County Soil and Vegetation Survey during the late forties, and by the subsequent studies of Gardner and Bradshaw (1954) and Mason's student McMillan (1956; 1964).

Need for an Ecosystem Concept

When it was discovered that pygmy forest grows on podsol soil, known locally as Blacklock soil, having a white, bleached surface horizon and an iron-cemented hardpan below it, naturalists indulged in an apparent *circulus vitiosus*. On field trips the professors of botany would tell their students that the podsol soil is the cause of the unusaul assortment of plant species, whereas the visiting professors of pedology (soil science) would attribute—in the light of classical podsol theory—the soil horizon features to the acid-producing vegetation. While it is true that a species individual responds to its soil niche, it is also true that it modifies that niche, which, in turn, reacts upon the individual. A broader approach is called for, the joint development of soil, vegetation and animal life with their mutual interrelated feedbacks (Jenny, 1961). It is embodied in the concept of the ecosystem.

Ecosystems Related to Land Forms

During Pleistocene times, when the continental glaciers formed and melted, the world-wide sea level sank and rose. The rising sea cut *terraces* into the prevailing graywacke sandstone rock. The retreating sea covered these platforms with beach sands, gravels and clays. Tectonic forces elevated the terraces. In this light, the higher terraces in the Mendocino area most likely are the older terraces.

Detailed field work between Navarro River and Fort Bragg led Gardner (1967) to assign terrace levels at altitudes of 100 ft., 175 ft., 300 ft., 425 ft. and 650 ft., corresponding to first, second, third, fourth and fifth terraces. These are the major terraces, according to our observations. The measurements do not refer to the actual terrace surfaces but to the hidden, buried "nickpoints" where terrace floor and sea cliff meet. Invariably, the pygmy forests and their associated extreme podsols are extensive on the three upper terraces (fig. 1).

The nearly level terraces are dissected by rivers that flow from the inland graywacke *mountains* westward to the sea. *Hill* and *canyon slopes* are continually being rejuvenated by a combination of slow geologic erosion (back cutting) and sandstone weathering. The slopes, mostly steep, are covered with impressive regional forests rich in redwoods and Douglas firs.

Besides these terraces, mountains and canyons a fourth landscape feature assumes prominence, the *sand dunes*. Wind is presently blowing graywacke-type sand from the beach up on to the adjacent higher first terrace, thereby placing fresh dune sand upon older, weathered and plant-covered beach deposit. What is happening today apparently happened in the past, for extensive sand dunes rest on all terraces. On the higher plateaus they have undergone intensive weathering and produced Noyo soils, but dune size and shape are largely preserved. Most important, the dunes on the lower terraces carry redwood and Douglas fir, those on the higher mainly bishop pines.

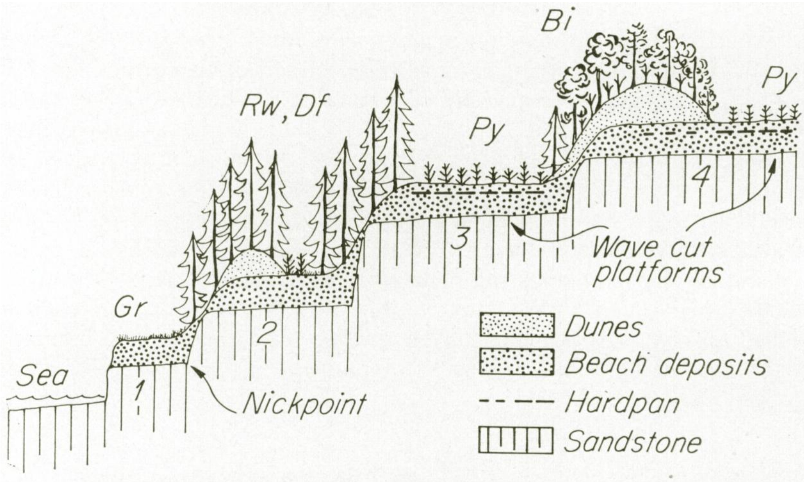

FIG. 1. Schematic arrangement of four marine terraces (1, 2, 3, 4) Fort Bragg area, with a young dune on second and very old dune on fourth terrace. Gr. = grassland, Rw, Df = redwood-Douglass fir forest, Bi = bishop pine forest, Py = pygmy forest. Horizontal distance is 3 miles, vertical distance 500 ft. above sea level.

To sum up, there is, then, a remarkable and fortunate mineralogical uniformity in the soil parent materials which are the initial states of the various forest soil ecosystems. They are either weathering graywacke sandstone or sandstone-derived beach materials and dunes. And though the land-form features fail to be uniquely reflected in vegetation discontinuities, they nevertheless bring out clearly the convergence of narrow endemism and dwarfism upon the higher and hence older land surfaces (*vetusta surfaces*). Their strongly podsolized soils provide niches for closed-cone pines and these niches also govern size and shape of the trees, tall bishop pines on Noyo soil and puny dwarfs on Blacklock soil.

THE PYGMY FOREST-PODSOL ECOSYSTEM

Among the various forest soil ecosystems along the coast the pygmy-podsol type has received most attention.

Vegetation mosiac. Extreme pygmy forest is species-poor and space-unsaturated, with as much as 25 per cent of the ground area bare or covered with colonies of lichen. Slender cypresses and gnarled and twisted bishop-and Bolander pines, many decades old and some passing the century mark, are only 1.5–3 m tall. Their trunk thicknesses do not exceed the diameter of a human wrist or arm.

Bolander pine was recognized as a distinct taxon, *Pinus bolanderi* Parl. by McMillan (1956). Critchfield (1957) designated it as a subspecies of *P. contorta.* Its leaves are narrowed, devoid of resin canals and the cones are heavier and asymmetrical. Unlike *P. contorta,* they are serotinous (closed-cone), a feature confirmed by plantings at the Institute of Forest Genetics, Placerville, California (personal communication by W. B. Critchfield). According to E. G. Linsley (personal communication) the cones harbor a longhorned beetle (*Paratimia conicola*) not observed on *P. contorta* but known from closed-cone pines in the dry interior Coast Range foothills (*P. attenuata*). Bolander pine is an advanced stage of ecotypic differentiation.It is an "edaphic" ecotype conforming to Turesson's definition.

Likewise dwarfed are the prominent ericaceous shrub companions, like *Ledum glandulosum* (Labrador-tea), *Rhododendron macrophyllum*) (rose-bay), *Gaultheria shallon* (salal), the two *Arctostaphylos* (manzanita) species, *nummularia* and *columbiana,* and *Vaccinium ovatum* (huckleberry). Trees and shrubs exhibit die-back symptoms and fungus-gall infestations suggestive of specific nutrient deficiencies. Indeed, chemical analysis of pine needles registers deplorable shortages of potassium, calcium, magnesium, and phosphorus (analyses by A. Ulrich).

The dwarf extremes are interspersed with clusters and thickets of taller pines and cypresses, in the 6–12m range, still with no signs of redwood or Douglas fir, though these giants prosper a short distance away. Occasionally, a statuesque bishop pine as high as 21m towers amidst the dwarfs.

Soil profile features. For an explanation of this living mosaic we must take a look at the underlying *Blacklock podsol* soil (fig. 2), a Typic Sideraquod. It is easier said than done. It takes two people with a sharp auger two to three hours to penetrate the dark-gray, 4-inch thick surface layer (A1 horizon), the 14-inch-thick bleached, white A2 horizon, and the concrete-like hardpan B-horizon (Bmir) which occupies the depth interval of about 18–30 inches. Below the pan is rusty, mottled sand or sandy loam, weakly cemented in places. At a depth of 5–10 ft. unaltered sandy beach material (C-horizon) is reached. It rests at 10–20 ft. on the impervious, sea-cut platform of hard sandstone.

The Blacklock surface soil is extremely acid, pH 2.8–3.9, one of the most acid soils known anywhere. It is low in available nitrogen and phosphorous, demonstrated already by McMillan (1956), and in potassium and micronutrients, as ascertained by elaborate pot tests in the greenhouses at Berkeley. The supply of the nutritionally important exchangeable calcium (Ca), magnesium (Mg) and potassium (K), expressed as milliequivalents in 100 g oven-dry soil, is exceedingly low. Above the hardpan the sum of these bases (Ca + Mg + K) is less than 1 meg/100g.

In stratified and finer textured beach materials of the old terraces a dense clay pan with up to 61% clay may occur instead of the iron cemented hardpan. It too acts as an effective impediment to root penetration. The bases are likewise low and mineral acidity is high. We are naming this soil *Aborigine*. A multitude of brown iron streaks and patches tint and mottle its clays.

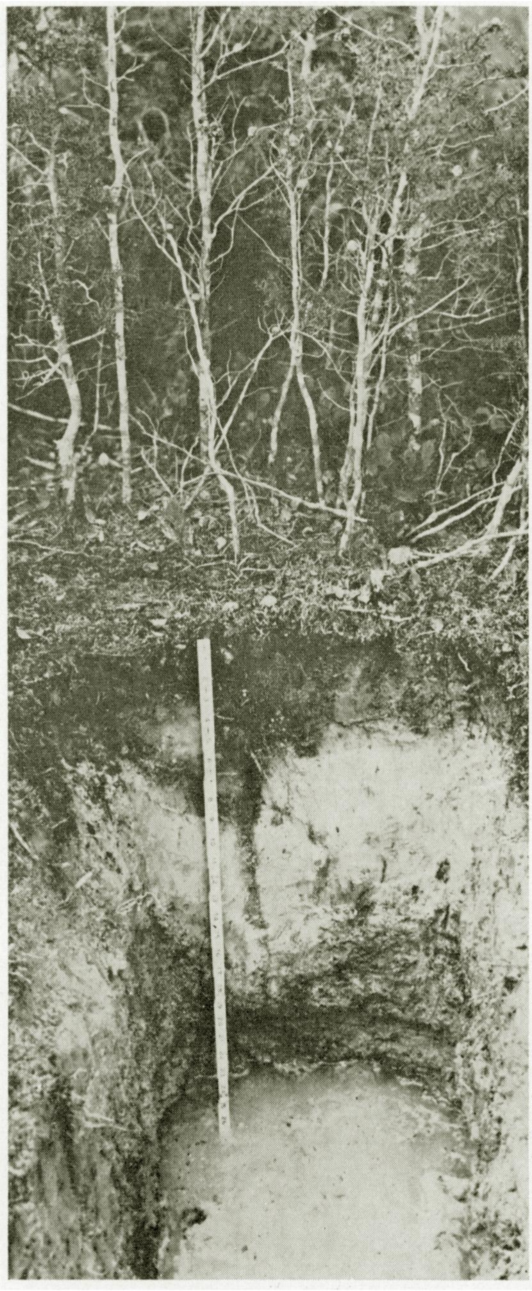

FIG. 2. Pygmy forest—podsol ecosystem. Cane-like *Cupressus pygmaea* growing on Blacklock soil showing surface humus horizon on white bleached A2 horizon which rests on iron hardpan. Water table is at 66 cm depth. Photo R. A. Gardner.

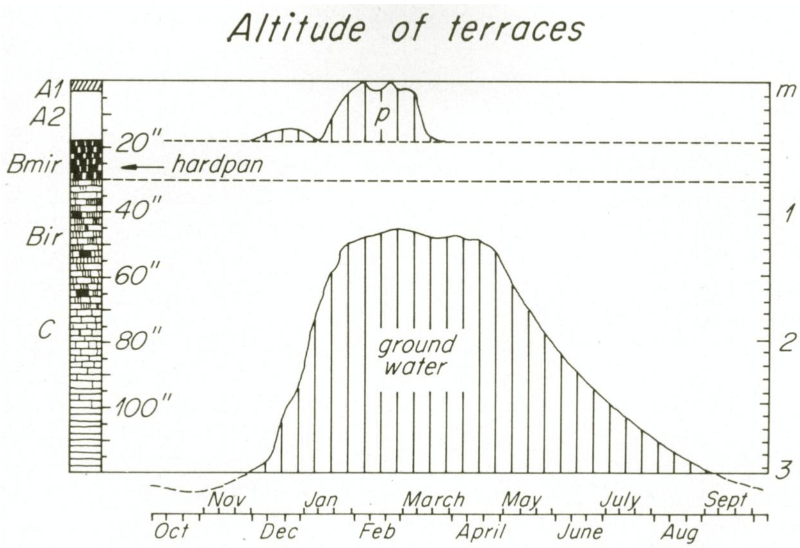

FIG. 3. Fluctuating water tables in Blacklock soil. Profile horizons indicated on left. During fall the water table is below 10 ft. After winter rains start a perched water table p above the hardpan is formed. The deep ground water table rises slowly to maximum height in February. During prolonged rains it may reach the hardpan. Mean annual precipitation is 38 inches.

Water regimen. If a 10 foot test hole is dug in the fall season, no free water is encountered. In early November, following the first 5–8 inches of winter rains, water begins to pile up on the basal rock plane and a rising groundwater table is set in motion. Long before it reaches the upper strata, water accumulates above the hardpan layer creating a second, perched water table (fig. 3) that floods the entire surface soil. In late spring the surface water table disappears by evapotranspiration and seepage. The soil down to the hardpan dries out, hardens and imparts extreme xeric conditions. In depressions and low places wetness persists throughout the rainless summer, giving rise to small sphagnum bogs. By October 1st, the descending ground water table has receded below the 10 ft.mark. Judging from about 40 permanent installations the rate of descent varies substantially among sites. Its correlation with the vegetation pattern has not yet been undertaken.

Podsolization process. As said, during the rainy season the surface soil is terribly wet and water stands in puddles and ponds. Its color is coffee brown from dissolved acid humus substances, their acidity originating from the carboxyl groups of pine needles and ericaceous leaves. The chelates of the humus combine with iron and other metals made accessible by weathering and render them mobile. Prior to and during hardpan formation the metal chelates (Fe, Mn) percolated and diffused into the subsoil, thereby bleaching and impoverishing the surface soil and leaving behind a snow white, thixotropic A2 horizon. This is podsolization. For reasons not yet fully understood, even though European investigators succeeded in imitating the process in the laboratory, iron may be precipitated in the subsoil as colloidal iron hydroxide. Its positive charge combines, according to a prominent theory, with the negatively charged soil particles cementing them together to an iron hardpan (Bmir of Blacklock). According to R. Tüxen (personal comment to Jenny) and Bloomfield (1965), iron migration is sensitive to the floristic composition of the plant cover. The process offers a promising challenge to an ecosystem-oriented biochemist.

Enclaves and borders. Within the pygmy forest area the taller pine and cypress thickets previously mentioned occupy fine textured (more clay, less sand) beach deposits but their clayey B-horizon is more permeable to roots than the severe Aborigine clay pan. The base status of lower horizons may be relatively high. The origin of this soil diversity is still obscure. One of the lone, impressive bishop pines surrounded by dwarfs had its root system exposed by chiseling away the hard A2 and indurated Bmir horizons. Surprisingly, an enormous tap root penetrated the hardpan and extended into the permeable deeper strata. Maybe there had been a crack or blemish in the pan, or the root was endowed with an exceptional supply of iron-dissolving chelates.

Seen from a distance, the change from pygmy to regional forest is very sharp. Vegetation appears discontinuous. Looking at the boundary more closely, 30–100 ft. wide transition zones (ecotones) disclose modulations of soils and plants. Where the canyon of Jug Handle Creek cuts into the fourth terrace (fig. 4) the drainage pattern is altered, the surface soil is deeper and moist in summer, and the hardpan is partially or entirely absent. At another site, an old sand dune rises rather abruptly above the pygmy plain. Its deep, weel drained soils offer a foothold to tall trees and thereby maintain a sharp vegetational contrast.

Multiple causes. In ecological parlance "edaphic causes" shape the appearance of vegetation. The adjective edaphic pertains to soil and its parent material. For Blacklock soil, what are the specific causes of endemism and dwarfism? Is it wetness in winter, dryness in summer, fluctuating water table, or is it oxidation or reduction, or harmful nitrite formation associated with the water regimen? Or, is it the impenetrable hardpan, either as a physical obstacle or as an unfavorable chemical environment? Or, is it high acidity or its related aluminum toxicity, or any one or all of the deficient nutrient elements in the spectrum of soil fertility? There is an enormous multiplicity of "causes," for thousands of soil properties are interrelated among each other, and with countless properties of the root system, and with enzymatic reactions and metabolic pathways inside the plant. It is a truly multivariate statistical problem, and we are approaching it in this light. We selected operationally soil variables that are amenable to manipulation and that are largely in-

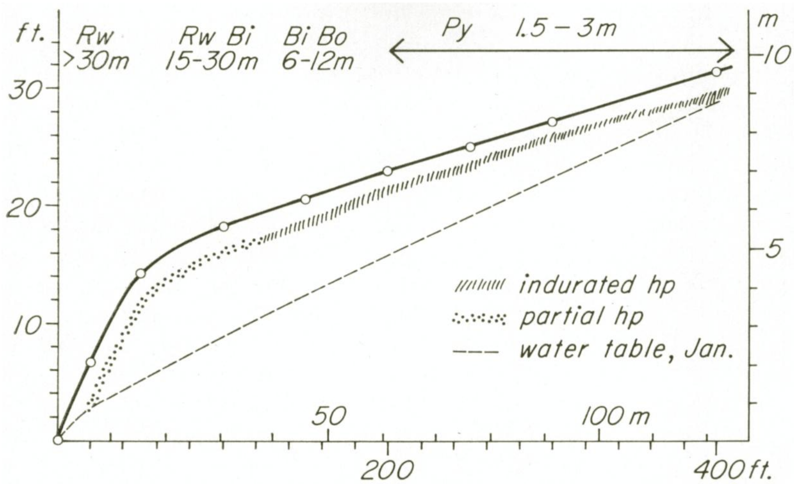

FIG. 4. Transition from pygmy (Py) forest on fourth terrace to regional forest in Jug Handle canyon. Circles indicate profile sites; water table as of Jan. 17; tree height in meters; Rw = redwood, Bi = bishop pine, Bo = Bolander pine. Vertical scale magnified.

dependent of each other (non-collinear). Thus, we initiated large-scale field experimentation on drainage with deep and shallow drains, randomized fertilization and breaking up of hardpan. So far, after a year's work, growth increments have been small, as one might expect for dwarfs. Mean elongation of five marked twigs on each of 80 pine trees was more than twice that of 80 cypresses. Also, elongations were larger on drained than undrained sites.

At any rate, this formidable array of soil attributes resulting from system evolution puts a tremendous strain on higher organisms. Redwood and Douglas fir do not grow and cypress and pines barely survive.

Genesis of Ecosystem and Its Significance for Endemism and Dwarfism

The staircase of terraces carpeted with beach materials and dune sand offers beautiful illustrations of ecosystem genesis. *The dune sequence* shall be taken up first.

On the lowest terrace, *recent dunes,* if bare, are still moving inland. Stabilization is brought about by colonizers, including lupines and *P. contorta* and *P. muricata.* The pines are able to endure strong salty winds, dry crests and winter-wet depressions. Slowly soil fertility is being built up.

Further away from the coast, as near Inglenook, the dunes on the second terrace (Lv-sites) are thousands of years old, but no C-14 dates are on hand. Dunes on the third terrace, Nm sites southeast of Cleone, might have been blown at the end of the last inter-glacial period or sometime thereafter. In all these *young dunes* oxidation has converted the originally drab, gray color of the recent dunes into a warm, rich brown. The minerals have weathered moderately, clay in amounts of 10–20% has been formed, and the exchangeable bases Ca + Mg + K are present in full measure, especially in the surface horizons (fig. 5). Acidity is around pH 5, considered advantageous for forest growth. All sites are covered with magnificent forest of redwoods, Douglas fir, grand fir (*Abies grandis*) and some western hemlock (*Tsuga heterophylla*). The soils abound in total nitrogen and in mildly acid humus, as exemplified by the carbon (C) – curve Lv in Fig. 6. These organic soil properties were not present at ecosystem time zero, the fresh dune, rather they are feed-back derivatives of the plant mantle on the one hand and the active microbial soil population — including the crucial nitrogen-fixers — on the other.

On the fourth and fifth terraces *very old dunes* are clearly recognizable. Sites specifically studied are labelled as Wi at 410 ft. altitude along Willits Road, and Dr at 560 ft. at the east end of Gibney Lane. The dunes are strongly weathered to great depth. The soils, known as Noyo, have podsolic features with a conspicuous, bleached, whitish A2 horizon underlain by yellow-brown, clay-rich B-horizons. The deeper subsoils may exhibit red-white reticulate mottling, a sign of profound chemical alteration. There is no hardpan though isolated iron concretions and cementations may appear in its place. During winter, water tables may be observed at depths greater than 10 feet.

The base content (Ca + Mg + K) is low (fig. 5, Wi, Dr), and soil reaction is sour, pH being around 4. Instead of mere humus acidity, as in Lv, Noyo's has a strong component of aluminum-rich clay acidity, said to be harmful to root growth. To a depth of 4 inches organic matter is enriched, but below that surface strip it drops to low magnitudes (fig. 6, Dr).

The dominant vegetation consists of sizable bishop pines, up to a century old, an isolated redwood tree here and there, and dense 1.5–3m tall underbrush of ericaceous species, joined by wax mytle (*Myrica californica*) and chinquapin (*Castanopsis chrysophylla*).

To summarize, the dune sequence expresses the transformation of the inert, fresh dune into a giant-tree ecosystem with an abundance of mild humus, a rich supply of bases, and advantageous quantities of soil acidity. This forest belongs to the major climax associations of the Coast Range (Heusser, 1960). Further soil transformations enhanced mineral acidity, depleted the stock of bases by leaching, and drained the humus reservoir to one-half by virtue of altered litter fall and soil microbe assembly. Gradually, the habitat became Noyo soil and the lush regional forest was displaced by endemic stands of closed-cone pine. From a utilitarian point of view, such as a lumberman's, the ecosystem deteriorated. If climax is defined (Cain, 1944) as a terminal plant community which is in dynamic equilibrium with the prevailing climate, then bishop pine rather than redwood forest would be climax on the dune. It explains in

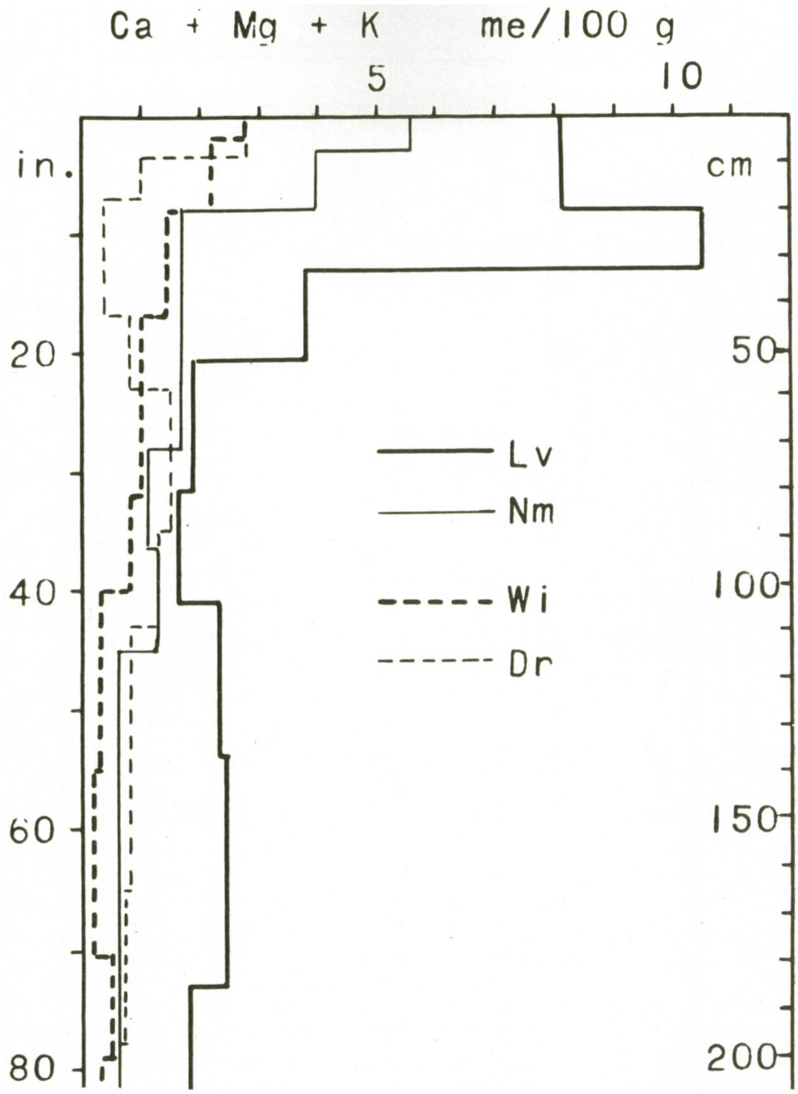

FIG. 5. Soil-depth curves of sum of exchangeable bases (me. of Ca + Mg + K in 100 grams of soil) for sand dunes of various ages. Lv is the youngest, Dr the oldest dune.

part the perpetuation of pine forests along the coast.

The parallel genesis of the *terrace soils* proper is accompanied by vegetation diversification of spectacular extent. New state factors entering into play are sluggish surface drainage, seasonal high water table, and texture extremes of beach materials ranging from sands to clays. When these materials were deposited their exchangeable bases had been in

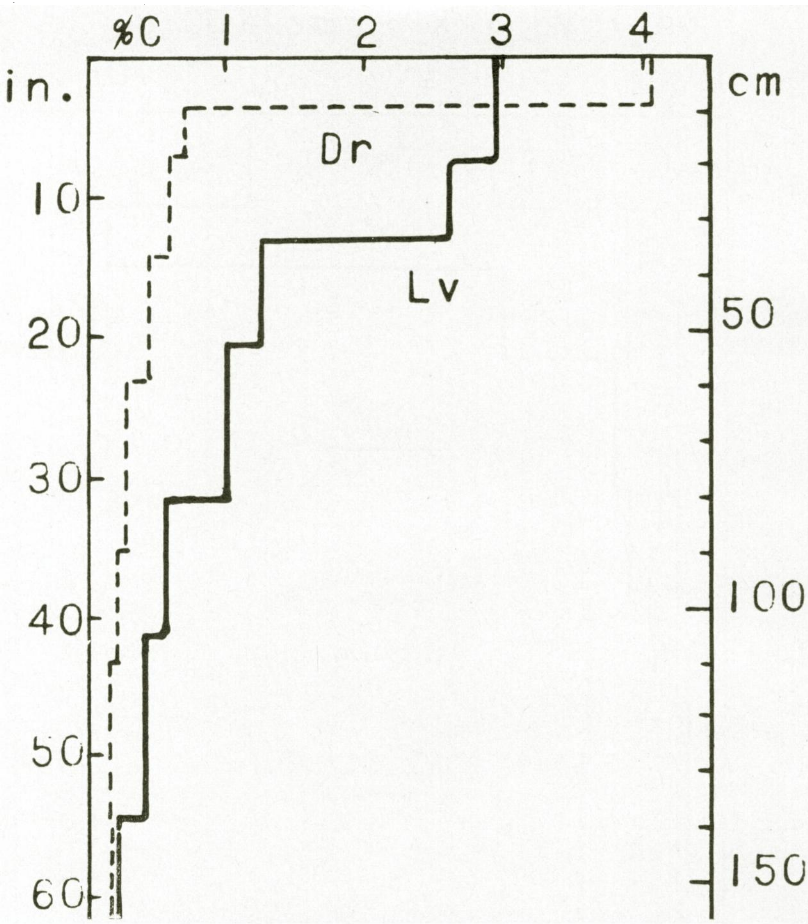

FIG. 6. Soil organic matter (mainly humus) expressed as percentage of organic carbon, in young (Lv) and very old (Dr) dunes in relation to soil depth.

chemical equilibrium with sea water which enriched their sodium content.

The *first terrace* supports grasslands and pine forests. Few redwoods, Douglas firs or hemlocks are seen. It appears that these trees cannot bear the local sea-salt and sodium challenge of air and soil. Under bishop pine in a sandy matrix Gardner (1967) sampled near Cleone a profile having a weakly bleached A2 horizon resting on a rusty colored sandy hardpan of weak cementation. It may be considered a precursor to Blacklock soil, the more so as its base content is relatively high.

East of Fort Bragg, the expansive *second terrace* displays wide ecosystem diversity. There are patches of tall redwoods on finer textured soil lacking wetness and A2 horizon but possessing an iron-stained clayey B. It might be a precursor to Aborigine soil. Nearby are tall, slender redwoods and hemlocks on waterlogged soil with A2 and iron concretions. Not far from it dense mixed stands of 12–18 m tall cypresses and bishop pines with an occasional redwood tree grow on bleached soil with iron nodule concretions. Last but not least, there is a tract of Blacklock soil with dwarfy forest devoid of commercial timber species.

On the *third and higher terraces* pygmy forest with pines and cypresses of various degrees of dwarfism is associated with Blacklock and Aborigine soils, as mentioned. In their sand fractions Gardner (1967) counted the slowly weathering potassium feldspar crystals (F) and the highly resistnet quartz grains (Q). In Fig. 7 the half circles on the vertical axis denote F/Q ratios of recent dune and beach materials. The white dots characterize the C-horizons of Blacklock soils on various terraces. In spite of the scatter of points, the trend (dashed line) confirms the mineralogical uniformity of the parent materials. Their mean is 17.5 K-feldspars per 100 quartz grains.

The black dots record F/Q of the Blacklock A2 horizons. The profiles of the older surfaces display exceedingly low ratios, less than 0.0003 for the fifth terrace. They signify far-gone weathering and they establish antiquity of soils, and, therewith, stability of the land forms. Moreover, the declining curve, in approaching zero, defines a terminal steady state condition. Barring a catastrophic change in state factors, we cannot visualize progression except perhaps for the trees getting more dwarfy.

It is tempting to view the evolution of the podsol ecosystems as an approximation to a monotone time-sequence operating in the cool and humid oceanic climate of the Fort Bragg area under conditions of tolerable salt influx. The initial state, the landscape situation at the start, comprises dune and terrace plus its biotic factor, the latter defined as the pool of species available to the site.

Today's biotic factor is made up of the germules offered by the regional forest and the coastal scrub and grasslands with an admixture of pine diaspores, particularly bishop-, shore- and Bolander pines. For the old Noyo, Blacklock and Aborigine soils the initial biotic factor might have included the Pleistocene ancestors of the pines. As the generations of seeds sprouted and grew the ensuing tree growth and vegetation differentiation responded to niche-creating soil development. Specifically, the emergence of dwarfism, severe ecotypes and local endemism became a consequence of orderly system evolution. It is not known on what soil type or types bishop pine evolved its genetic constitution, but that of Bolander pine presumably developed in conjunction with Blacklock and Aborigine soil genesis.

Natural vegetation sequences of the order of magnitude here envisioned are customarily attributed to a climatic shift. While we do recognize climatic changes in the Mendocino area, we do not believe them to be critical. Even if effective moisture had been doubled or reduced, it would have merely temporarily accelerated or retarded the long-time podsolic trend that molded both phenotype and genotype.

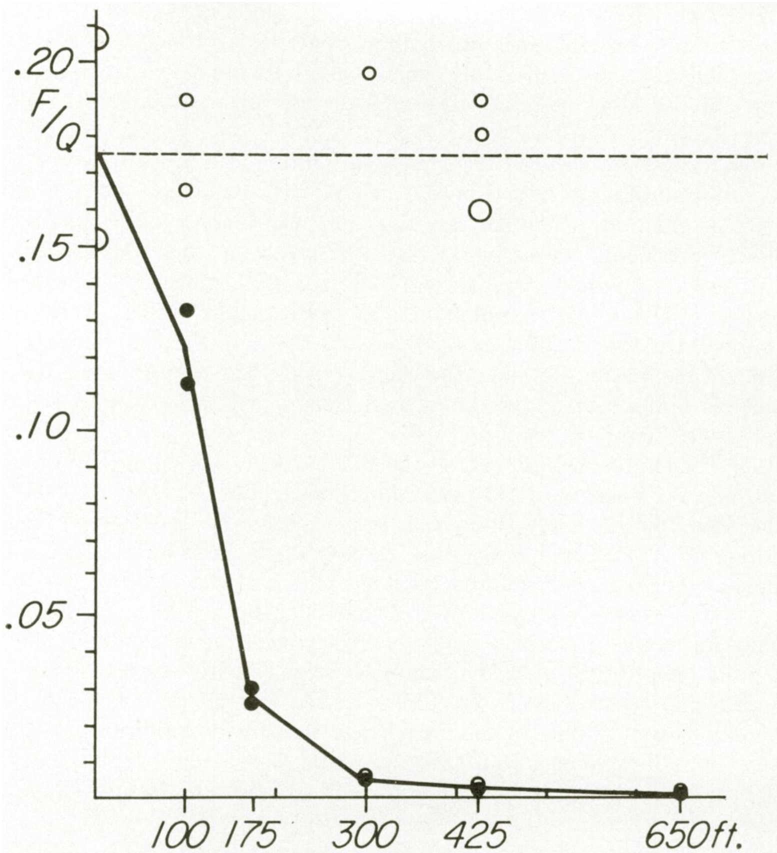

Fig. 7. Ratios of per cent K-feldspar (F) and per cent quartz (Q) in the sand fractions of parent materials (white dots) and in Blacklock A2 horizons (black dots). Parent material averages 17.5 feldspar to 100 quartz grains. The lower the ratios the more weathering has occurred.

The Age Problem of the Podsol Ecosystem

Heusser (1960) published a pollen profile of a boggy site in the pygmy forest southeast of Fort Bragg. Bolander pine was prominent throughout the span of some 6,000 years. Redwood can be traced to much earlier periods as buried trees are frequently encountered by well drillers. A log was found at 16 ft. depth at the base of the Nm dune which sits on the front edge of the third terrace.

If the origin of the first terrace is correctly interpreted, its cutting was completed at the onset of the Wisconsin glaciation, some 100,000 years ago. If the higher terraces are also linked to glacial periods, time spans up to one million and more years could be involved (middle or early Pleistocene). These estimates pertain to the rock-cut terrace platforms.

Owing to erosion and deposition, the soils on a terrace might be younger than the platform itself. Also, since the classic podsols of northern Europe are all post-glacial, podsolization is a relatively fast process. Still, none of the German and Scandinavian profiles and their plant cover even approaches the extreme hardpan and dwarfism of the Mendocino Blacklock ecosystem.

The low F/Q quotients of Fig. 7 prove advanced age of soils but they do not elucidate the age of the profile features, specifically of the hardpan. In a clever piece of detective work, Gardner (1967) answered the query for site Wi where an extensive old dune rests on the fourth terrace. It was blown in when the sea level stood at the third terrace. Gardner dug a vertical shaft into the dune. At 13 ft. depth the deeply weathered mantle faded rapidly into unaltered dune material, its slip faces still intact. Their inclinations were identical with those of today's fresh dunes, and so was their orientation as to wind direction. At 20 ft., at the unweathered base of the dune, a light-gray horizon was underlain by a rusty-streaked, irregularly cemented hardpan, the two strata identifying a Blacklock precursor. No wood remains showed up.

Podsolization on the high terrace must have started prior to dune deposition, and though the process became arrested under the dune, it continued outside, for Blacklock exists there now. Gardner (1967) devised a speculative mathematical model of the weathering process that predicted a soil age of about a million years on the highest terrace. The order of magnitude seems plausible.

To conclude, not only the terraces themselves but their soil profiles too possess a venerable age For how long today's Blacklock and Aborigine profiles have capped the terrace mantle is not known. Because of its age and extreme features the pygmy forest-podsol ecosystem is unique in the temperate region, and it comes as close to a terminal steady-state system with balanced inputs and outputs as can be expected to be found in nature. It deserves further intensive investigation. To do so, suitable sites must be protected as scientific reserves. It is an urgent task that demands highest priority (Jenny, 1960).

Summary

1. Along the coast of northern California, the higher, older marine terraces carry pygmy forest, and the associated old sand dunes are covered with bishop pines. The lower, younger terraces and dunes support grasslands, pines, and redwood-Douglas fir forest.

2. Pygmy forest consists of small cypresses (*Cupressus pygmaea*), dwarfed, closed-cone pines (*Pinus muricata* and *P. contorta* ssp. *bolanderi*) and stunted ericaceous associates, growing on extreme podsol soil having a bleached, white A2-horizon underlain by an indurated iron hardpan. During millennia vegetation and soil have evolved together (pygmy forest-podsol ecosystem).

3. Two sequences of podsolization are envisioned, both starting on

sandy parent materials: a. *Dunes*. Younger dunes, in contrast to unaltered recent dunes, are slightly weathered. They are high in bases and humus, low in clay acidity and they support luxurious redwood-Douglas fir forest. Continual weathering and leaching in the cool and humid oceanic climate impoverishes the soil and augments acidity. Through time the regional forest is gradually replaced by endemic bishop pines. b. *Terraces*. On the level plateaus with high, fluctuating water tables the podsolic processes are intensified, resulting in hardpans and clay pans and soil conditions that produce dwarfism, narrow endemism and pronounced ecotypic differentiation.

4. Geologic considerations and soil weathering indices provide age estimates of several hundred thousand years. The pygmy forest and its podsol soil comes as close to a terminal steady-state ecosystem as can be expected to be found in nature. Adequate preservation is urgent.

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Department of Soils and Plant Nutrition, and School of Forestry
and Conservation, University of California, Berkeley

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