same interaction rules as subluminal quanta but only as completely uncontrollable fluctuations. Such a possibility was mentioned by Terletskii (*12*). There is no fundamental objection to such a speculation. It does, however, raise the question of the meaning of the statement "tachyons exist." How would one verify that such fluctuations travel faster than light? How, indeed, could such tachyons be discovered? If one found them, how would he know that he had found them?

Conclusion

The conclusion we draw from this discussion is not that it is impossible for superluminal particles to exist but that, if they were found and meaningfully identified as such, the consequences for physics would be far-reaching. Either relativity theory or basic rules of quantum mechanics would have to go by the board, or else some very fundamental assumptions of the essential controllability of events would have to be abandoned. The final answer, of course, rests with the experimentalist.

References and Notes

1. A. A. Michelson and E. W. Morley, *Phil. Mag.* **24**, 449 (1887).
2. Because of the postulated universal constancy of their speed, light signals can easily be used to synchronize distant clocks that are at rest with respect to each other. Contrary to some statements in the literature, it is the universal constancy of the speed of light that makes light signals uniquely suitable for this task. That the speed of light is the highest possible signal velocity is not an assumption, nor did Einstein postulate it in his famous paper introducing the special theory of relativity [*Ann. Phys.* **17**, 891 (1905)]. He used postulates (i) and (ii).
3. It is sometimes stated that this motion is *backward in time*. Such terminology is of doubtful meaning and obscures the simple issue.
4. This conclusion, based on the same grounds, seems to have been drawn first by R. C. Tolman, in *The Theory of the Relativity of Motion* (Univ. of California Press, Berkeley, 1917), p. 54.
5. It is easy to avoid the periods of acceleration by using four rockets and two additional signals from one rocket to an immediately adjacent one.
6. For example, D. Bohm, *The Special Theory of Relativity* (Benjamin, New York, 1965), p. 158.
7. I am assuming here that things are sufficiently isolated so that the other occurrences of *B* do not swamp the occurrences of interest, and true events could be assigned to chance coincidences. Another caveat: In view of quantum mechanical relaxation of strict causal connections, one would not try to establish invariable correlations between *A* and *B* but only statistical correlations. The principle would remain unaltered.
8. This is the position of P. L. Csonka ("Causality and Faster than Light Particles," preprint, 1969).
9. G. Feinberg, *Phys. Rev.* **159**, 1089 (1967). Earlier papers on superluminal particles: S. Tanaka, *Progr. Theor. Phys. (Kyoto)* **24**, 171 (1960); O. M. P. Bilaniuk, V. P. Deshpande, E. C. G. Sudarshan, *Amer. J. Phys.* **30**, 718 (1962). Published simultaneously with Feinberg's paper: D. Kroff and Z. Fried, *Nuovo Cimento* **52A**, 173 (1967). The paper by Bilaniuk *et al.* is based on classical arguments alone, and the other two are concerned with quantum fields. All three of these papers ignore the problem of causal cycles. Subsequent papers on superliminal particles are: R. G. Newton, *Phys. Rev.* **162**, 1274 (1967); R. Fox, C. G. Kuper, S. G. Lipson, *Nature* **223**, 597 (1969); W. B. Rollnick, *Phys. Rev.* **183**, 1105 (1969); and others referred to below.
10. T. Alväger and M. N. Kreisler, *Phys. Rev.* **171**, 1357 (1968).
11. This reversal of emission and absorption is called the reinterpretation principle by O. M. Bilaniuk and E. C. G. Sudarshan [*Phys. Today* (May 1969)] and is called the switching principle by E. C. G. Sudarshan [preprints SU-1206-186 and SU-1206-191 (December 1968)].
12. Ya. P. Terletskii, *Paradoxes in the Theory of Relativity* (Plenum, New York, 1968).

13. Supported in part by the National Science Foundation.

Postglacial Vegetational History of the Great Plains

New evidence reopens the question of the origin of treeless grasslands.

Philip V. Wells

Increasing numbers of late Pleistocene macrofossil and pollen records from the Great Plains or Plains border indicate that boreal spruce forest similar to the existing taiga in Canada was present on the northern Plains at that time. Dated records of spruce (*Picea*) are scattered over a wide extent of what are now mainly grasslands from the plains of southern Saskatchewan south to northeastern Kansas, and from western Minnesota south to western Missouri (Fig. 1). Macrofossils accompanying the abundant coniferous pollens include needle-leaves, seeds, or cones of spruce (Table 1). The white spruce [*Picea glauca* (Moench) Voss] grew on high ground of the coteau near Moose Jaw, Saskatchewan, as recently as about 10,270 years ago (according to radiocarbon dating) (*1*), on morainal deposits south of Tappen in central North Dakota about 11,500 years ago (*2*), and in the sand hills of southwestern South Dakota, near the Nebraska line, about 12,600 years ago (*3*). There were high percentages of spruce pollen and macrofossils of spruce and tamarack (*Larix laricina*) at a number of sites near the western border of Minnesota (*4*), and at Pickerel Lake in eastern South Dakota, where the coniferous material lies just below a level dated at about 10,700 years ago (*5*). Spruce was present as far south as Muscotah Marsh in northeastern Kansas (*6*), and in spring deposits near the edge of the prairie on the Ozark Plateau in southwestern Missouri, where macrofossils and pollens of spruce and *Larix* are associated with radiocarbon dates ranging from about 13,700 to 16,600 years ago; the second of these determinations was made on a spruce log (*7*).

Some of the late-Wisconsin spruce sites on the Plains are as much as 750 kilometers (465 miles) from the nearest existing stands of spruce (Table 1), but even the southernmost sites are less than half that distance from terminal moraines marking the maximum advance of the late-Wisconsin ice sheet; the northern sites are on glaciated terrain. The indicated latitudinal extent of spruce-dominated vegetation on the northern Plains at the close of the Wisconsin glacial was about the same as, or less than, the width of the present boreal coniferous zone in Canada.

In now relatively arid southwestern Kansas (Meade County) and adjacent

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Oklahoma, deposits of Illinoian, Sangamon (interglacial), and Wisconsin age have yielded high relative percentages of pine pollen (up to 90 percent) but only small amounts of spruce pollen and no spruce macrofossils (*8*). In the northern part of the Texas panhandle near Channing, about 260 kilometers to the southwest, the Rita Blanca deposits of earlier Pleistocene (Blancan) age have yielded leaves of deciduous white oaks resembling the sand post oak, *Quercus stellata* var. *margaretta* (Ashe) Sarg. The associated pollen profile shows more than 50 percent sagebrush (*Artemisia*) pollen (*9*). At present the nearest post oaks (*Q. stellata* Wang.) grow with shin oak (*Q. havardii* Rydb.) and hybrids resembling *Q. stellata* var. *margaretta* on sand hills at the eastern edge of the Texas panhandle, about 200 kilometers east of the Rita Blanca site. The sand sagebrush (*A. filifolia* Torr.) is a dominant shrub on sandy soils in the Texas panhandle today.

On the still more arid plains of the Llano Estacado in the southern part of the Texas panhandle, several pollen profiles from Wisconsin-age sediments record very high content of pine pollen (more than 90 percent) and low content of spruce pollen (10 percent or less). A pollen spectrum of this type from Rich Lake near the southern edge of the Llano is associated with a radiocarbon age of about 17,400 years (*10*). Unfortunately it has not been possible to establish the identity of the pines recorded at the fossil pollen sites on the southern Plains. However, macrofossil evidence has been obtained on the southwestern border, about 400 kilometers south of Rich Lake. Beautifully preserved plant materials with radiocarbon ages ranging from 11,500 to more than 20,000 years are abundant in numerous rock-sheltered wood-rat (*Neotoma*) deposits at what are now desert elevations in southwestern Texas (*11*). Even in now very arid reaches of the Chihuahuan Desert, pine-dominated vegetation was widespread during the Wisconsin glacial, but the pine was a xerophytic variety of the Mexican piñon (*Pinus cembroides* var. *remota* Little). The fossil evidence from the southwestern edge of the Stockton Plateau, adjacent to the Plains, indicates that the piñon pine formed an open woodland with live oaks and juniper, together with cacti, Agavaceae, and other light-demanding, semidesert plants. Some grass fruits representing four genera (*Bouteloua, Buchloe, Het-*

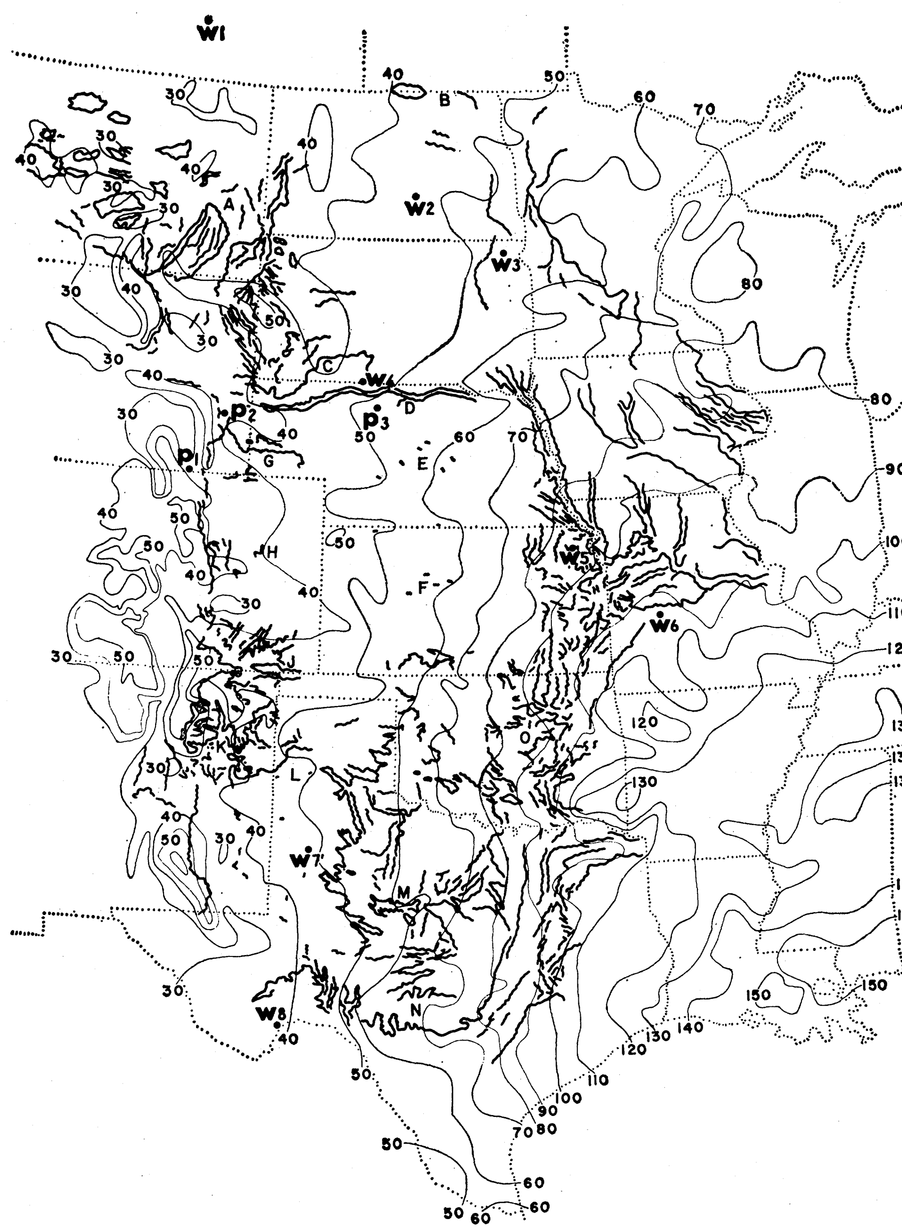

Fig. 1. Location of late-Wisconsin (W) and postglacial (P) fossil records of forest or woodland vegetation in relation to distribution of existing nonriparian, scrap woodlands (heavy lines) in the Great Plains region. Thin, continuous lines are isohyets at 10-centimeter intervals, ranging from 30 to 150 centimeters of mean annual precipitation. Dotted lines indicate state or other boundaries. (W1) Hafichuk Ranch, southwest of Moose Jaw, Saskatchewan; (W2) 16 kilometers south of Tappen, Kidder County, North Dakota; (W3) Pickerel Lake, Day County, South Dakota; (W4) 30 kilometers southwest of Rosebud, Todd County, South Dakota; (W5) Muscotah Marsh, Atchison County, Kansas; (W6) Boney Spring, Benton County, Missouri; (W7) Rich Lake, Terry County, Texas; (W8) Maravillas Canyon and Dagger Mountain, Brewster County, Texas; (P1) southwestern corner of Laramie Basin, Albany County, Wyoming; (P2) 3 kilometers southeast of Guernsey, Platte County, Wyoming; (P3) Hackberry Lake, Cherry County, Nebraska. Some dominant upland tree species of existing scarp woodlands from selected areas of the Plains, indicated by smaller letters A to O, are as follows: (A, C, D, G, H) *Pinus ponderosa, Juniperus scopulorum*; (B) *Populus tremuloides* Michx., *Quercus macrocarpa* Michx.; (D, E) *P. ponderosa, virginiana* L., *Q. macrocarpa*; (F) *J. virginiana*; (J, K) *P. ponderosa, P. edulis* Engelm., *J. monosperma* (Engelm.) Sarg., *J. scopulorum, Q. undulata* Torr.; (L) on northwest, similar to J and K, but lacking *P. ponderosa*; (L) on east (Break of the Plains), *J. pinchotii* Sudw., *Q. mohriana* Buckl.; (M, N) *Q. virginiana* L., *Q. shumardii texana* Ashe, *Q. mohriana, J. ashei* Buchholz, *J. pinchotii*; (O) *Q. stellata* Wang., *Q. marilandica* Muenchh.; *Q. muehlenbergii* Engelm., *Q. shumardii, J. virginiana.*

Table 1. Pollen and macrofossil records of forest or woodland vegetation during late Wisconsin time, 10,000 to 20,000 years ago, in what is now grassland or desert in the Plains region of central North America.

Fossil site	Radiocarbon dates (years ago)	Pollen (%)		Macrofossils	Distance (km) from existing stands of trees		Reference
		Spruce	Pine		Spruce	Pine	
Moose Jaw, Saskatchewan	10,270 ± 150 11,650 ± 150	55	20	Spruce	160	250	(*1*)
Tappen, North Dakota	11,480 ± 300			Spruce	300		(*2*)
Rosebud, South Dakota	12,580 ± 160	70	10	Spruce	200	20	(*3*)
Pickerel Lake, South Dakota	>10,670 ± 140	85	5	Spruce, larch	160	160	(*5*)
Muscotah, Kansas	15,500 ± 1500	70	10	Spruce	700	320	(*6*)
Boney Spring, Missouri	13,700 ± 600 16,580 ± 220	36	5	Spruce, larch	750	100	(*7*)
Rich Lake, Texas	17,400 ± 600	10	90		320	200	(*10*)
Maravillas Canyon,* Texas	14,800 ± 180			Pine (piñon), oak, juniper		50	(*11*)
Dagger Mountain,* Texas	16,250 ± 240 20,000 ± 390			Piñon, oak, juniper		40	(*11*)

* Sites of maximum aridity, at latitude (29°30′N) and elevations (600 and 800 meters) now occupied by desert vegetation.

eropogon, and *Tridens*) also entered the *Neotoma* record, evidence of their coexistence with woodland conifers then as they coexist today in grassy woodland on high mountains within the Chihuahuan Desert province (*11*). On the other hand, there is no indication that *treeless* grassland shifted southward into what is now the arid Chihuahuan Desert during the Wisconsin glacial, when much of the Great Plains south of the ice sheet was occupied by coniferous forest, woodland, or possibly parkland.

At most of the fossil pollen sites in the Plains region there is a dramatic decrease in coniferous pollens in the postglacial sediments that is usually interpreted as a climatically induced shift to a more xerophytic, nonarboreal vegetation similar to the prairies of today. However, dated pollen evidence on the postglacial history of vegetation and climate in the grassland province is relatively scanty and ambiguous (*5, 12*).

Biogeographic Evidence

The extensive migration of boreal or cool-temperate tree species during the Wisconsin glacial has left a record in the existing flora of the Plains region. The white spruce (*Picea glauca*) persists today in the northern Plains as isolated populations in the Black Hills of South Dakota (*13*) and the Cypress Hills of southern Alberta and Saskatchewan (*14*), and the balsam fir [*Abies balsamea* (L.) Mill.] has disjunct, relictual populations as far south as northeastern Iowa (*15*). Some of the boreal deciduous trees that occur in the Black Hills—the paper birch (*Betula papyrifera* Marsh) and the aspen (*Populus tremuloides* Michx.)—range disjunctly southward in the Plains to the canyons of the Niobrara River and the Sandhills of Nebraska (*16*).

Postglacial migration may be implied by the more or less disjunct distributions of temperate deciduous species in the western sector of the northern Plains. In the Black Hills, for example, the bur oak (*Quercus macrocarpa* Michx.), the hop hornbeam [*Ostrya virginiana* (Mill.) Koch], the American elm (*Ulmus americana* L.), and two species of hazel (*Corylus americana* Walt. and *C. cornuta* Marsh) form an isolated outlier of the eastern deciduous forest (*13*). The disjunct occurrence of a race of the sugar maple (*Acer saccharum* Marsh) in the Caddo County canyons and the Wichita Mountains of western Oklahoma (*17*) may have a similar history, or may be older.

Evidence of hybridization between the now widely separated eastern bur oak (*Quercus macrocarpa*) and the western Gambel oak (*Q. gambelii* Nutt.) indicates a relatively recent sympatry in New Mexico and South Dakota (*18*). The southern hybrid populations are small and isolated in the canyon of Tramperos Creek, well out on the short-grass steppe of northeastern New Mexico. The hybrids are in contact with the western parent, *Q. gambelii*, a seemingly unstable situation, but they are 400 kilometers to the west of the existing range of bur oak in Oklahoma. The disjunction is analogous to that of the isolated sugar maple populations of western Oklahoma, inasmuch as a climate less arid than the present one would account for the implied westward migration. However, extensive introgression of the large populations of bur oak in the Black Hills of South Dakota suggests a massive *northward* migration of the Gambel oak. Since the present northern limits of the less cold-tolerant Gambel oak are in the central Rocky Mountains, about 400 kilometers to the southwest, a postulated northeastward migration of *Q. gambelii* across the intervening plains to the outlying Black Hills requires a climate both *warmer* and wetter than the present one, thus ruling out a Wisconsin or earlier glacial age for the indicated distribution. Any then-living evidence of older incursions of the Gambel oak into the Black Hills almost certainly would have been eliminated during the now well-documented spruce maximum of the late Wisconsin glacial in South Dakota, dated as recently as about 11,000 to 12,000 years ago. Hence, a postglacial incidence of warm-moist climate is implied for the northern Great Plains.

A Postglacial Macrofossil Record of Coniferous Woodland

There is a remarkable record of coniferous woodland during the latter half of postglacial time on the floor of the Laramie Basin in southeastern Wyoming. The record consists of plant macrofossils ranging in size from massive logs of western red cedar (*Juniperus scopulorum* Sarg.) up to 1.3 meters (4 feet) in diameter—exposed at the surface or partly buried in shallow sand deposits—to leaves, cones, and seeds of red cedar and ponderosa pine (*Pinus ponderosa* var. *scopulorum* Engelm.), preserved in ancient, rock-sheltered, wood-rat middens. The Laramie Basin (Fig. 1) is partially enclosed on the east, west, and south by high mountains that create a pronounced local rain-shadow, and the extensive plain on the floor of the basin is now even more arid than the treeless grasslands of the High Plains to the east of the Front (or Laramie) Range of the Rocky Mountains in southeastern Wyoming. The mean annual precipitation at Laramie is only 30 centimeters (12 inches).

Existing vegetation. The upland vegetation in the vicinity of the subfossil materials, located in the arid southwestern corner of the Laramie Basin about 30 kilometers south of Laramie, may be described as a shrub-steppe. The flat plains on the floor of the basin are covered with a short-grass sod of blue grama (*Bouteloua gracilis* H.B.K.) and a sparse scattering of dwarf sagebrush [*Artemisia arbuscula* ssp. *nova* (Nels.) Ward and *A. frigida* Willd.]. On the eolian sand deposits, the vegetation is dominated by the large silver sagebrush (*A. cana* Pursh), with reduced numbers of these other species (*19*). Not only is the prevalent vegetation at the site desertic in physiognomy but it bears a strong floristic resemblance to the winter-cold deserts of the Great Basin and the Colorado Plateau (*19*). Nevertheless, at one spot below a particularly massive, gently sloping surface of sandstone bedrock, three individuals of western red cedar (*Juniperus scopulorum* Sarg.) were surviving in 1968, though they appeared to be dying back in response to the severe droughts of recent decades. The three junipers are isolated here in a microsite uniquely favored by catchment of runoff from an extensive area of bare rock slope, but even so the present conditions must be near their tolerance limits. The general lower limit of coniferous timber on mountains surrounding the arid south end of the basin is about 300 meters higher, at an elevation of about 2560 meters. The last surviving junipers apparently provide a living sample of a vegetation that used to be extensively distributed on the floor of the basin but is now represented mainly by beautifully preserved subfossil plant materials.

Former vegetation. The numerous sandstone outcrops in the southern part of the Laramie Basin have an extraordinary development of cavities and rock shelters that harbor many ancient wood-rat middens. The bulk constituents of the deposits from an area several kilometers square are uniformly *Juniperus scopulorum* Sarg., represented by leafy twigs and wood. Two of the middens, with radiocarbon ages of 1860 ± 80 and 4060 ± 80 years, also contain two-needled leaf fascicles of another conifer, *Pinus ponderosa* var. *scopulorum* Engelm. The pine, like the juniper, no longer grows at the *Neotoma* sites, although it is present on mountain slopes rimming the basin, and in a canyon on the basin floor. On the other hand, most of the other species represented in ancient *Neotoma* deposits are still growing at or near the sites of deposition. Of the 15 species identified in seven dated middens (Table 2), 13 are xerophytic shrubs or herbs that are more or less widely distributed on the floor of the basin and lend a semidesert character to the existing vegetation (*19*). In particular, the species of *Artemisia, Atriplex, Chrysothamnus, Eurotia,* and *Oryzopsis* are characteristic of the winter-cold deserts of western North America. The composition of the old *Neotoma* middens corresponds to an open, xerophilous woodland dominated by the western red cedar and by fewer trees of ponderosa pine, with a lower synusia of semidesert shrubs and grasses. The recent decline of the woodland conifers to the vanishing point indicates a dramatic shift in the physiognomy of the vegetation from woodland to semidesert shrubland, but the floristic composition shows remarkably little change during the past 4000 years, aside from the local demise of the conifers.

Table 2. Summary of semiquantitative analysis of plant remains in the oldest *Neotoma* deposit (radiocarbon age, 4060 ± 80 years) among the seven dated middens from the southwestern corner of the Laramie Basin. The other middens show a similar composition, with the notable exception of content of *Pinus ponderosa*, a species which appears in only one other dated deposit (radiocarbon age, 1860 ± 80 years).

Species	Structures	Relative abundance*
	Trees	
Juniperus scopulorum Sarg.†	Leafy twigs, seeds	+++
Pinus ponderosa var. *scopulorum* Engelm.†	Leaves, cone-scales	++
	Shrubs	
Rhus trilobata Nutt.	Seeds, leaves	++
Artemisia cana Pursh	Leaves	+
Atriplex canescens (Pursh) Nutt.	Winged fruits	+
Cercocarpus montanus Raf.	Leaves, fruits	+
Chrysothamnus viscidiflorus (Hook.) Nutt.	Involucres, achenes	+
Eurotia lanata (Pursh) Moq.	Leaves, fruits	+
Prunus besseyi Bailey	Endocarps	+
	Agavaceae, Cactaceae	
Yucca glauca Nutt.	Capsules, seeds, leaves	+++
Opuntia polyacantha Haw.	Areoles, seeds	++
	Grasses and forbs	
Oryzopsis hymenoides (R. & S.) Ricker	Fruits	++
Stipa comata Trin. & Rupr.	Fruits	+
Lappula fremontii (Torr.) Greene	Nutlets	+
Lithospermum incisum Lehm.	Nutlets	+

* Symbols for relative abundance: +, low; ++, intermediate; +++, high. † Species no longer growing in vicinity of deposit.

An outstanding feature of the paleoecological record at this locality is the presence of old wood of *Juniperus scopulorum* at or near the surface of the extensive sandy flats on the floor of the basin. The logs are widely scattered over an area several kilometers square in the vicinity of the ancient *Neotoma* sites. Despite the fact that the exposed wood ranges in radiocarbon age from about 200 to 1700 years, the logs are remarkably well preserved, and even the strong fragrance of terpenes that is characteristic of red cedar wood is retained. Weathering is limited to complete removal of the shreddy bark and graying of the outermost wood; charring was observed on only one log. Persistent stubs of branches and roots indicate little or no transport.

Some of the logs are gigantic by present standards, the largest having a massive trunk more than 1.3 meters in diameter (Fig. 2). A ring count of a 0.5-meter section at the apical end of the main axis showed about 450 growth rings, implying a life span of as much as 1000 years for the tree. The radiocarbon age of the outermost sapwood records the approximate time of death of the tree—in this instance, 940 ± 105 years ago (GX-1407). Hence, the largest juniper log should yield a dendrochronology covering the greater part of the first millennium A.D.

The radiocarbon ages of the outermost sapwood of ten juniper logs at as many different sites on the surface of the eolian sand deposits range from a remarkably recent 205 ± 95 years to 1735 ± 80 years. Thus the massive logs elegantly corroborate the more detailed macrofossil evidence in the seven dated *Neotoma* middens as to the former abundance and extent of juniper woodland on the floor of the basin dur-

Table 3. Radiocarbon chronology of woodland conifers on the floor of the Laramie Basin at sites where no conifers exist today. Dating of the juniper logs was based on outermost sapwood; dating of the *Neotoma* middens was based chiefly on the abundant coniferous plant material. The radiocarbon ages were determined at the Institute of Geophysics, University of California, Los Angeles (UCLA), and at Geochron Laboratories, Inc., Cambridge, Massachusetts (GX).

Radiocarbon age (years)	Sample number	Paleoecological significance
	Log of Juniperus scopulorum Sarg.	
205 ± 95	GX-1406	Death of juniper tree
385 ± 85	GX-1400	Death of juniper tree
580 ± 105	GX-1405	Death of juniper tree
735 ± 95	GX-1404	Death of juniper tree
790 ± 95	GX-1408	Death of juniper tree
940 ± 105	GX-1407	Death of juniper tree
1060 ± 75	GX-1401	Death of juniper tree
	Neotoma midden, abundant juniper	
1100 ± 80	UCLA-1406	Presence of *J. scopulorum*
	Log of J. scopulorum	
1145 ± 80	GX-1402	Death of juniper tree
1445 ± 95	GX-1403	Death of juniper tree
	Neotoma midden, abundant juniper	
1600 ± 80	UCLA-1404	Presence of *J. scopulorum*
	Log of J. Scopulorum	
1735 ± 80	UCLA-1098E	Death of juniper tree
	Neotoma midden, abundant juniper	
1860 ± 80	UCLA-1098A	Presence of *Pinus ponderosa* var. *scopulorum* and juniper
2020 ± 80	UCLA-1405	Presence of *J. scopulorum*
2320 ± 80	UCLA-1098D	Presence of *J. scopulorum*
2900 ± 80	UCLA-1098C	Presence of *J. scopulorum*
4060 ± 80	UCLA-1098B	Presence of *Pinus ponderosa* var. *scopulorum* and juniper
	Log of J. scopulorum	
5625 ± 140	GX-1426	Death of juniper tree

ing the overlapping time interval from about 1100 to 1800 years ago (Table 3). A uniquely sheltered juniper log, lodged in a rock crevice and partly buried by a more recent *Neotoma* deposit, has a radiocarbon age of 5625 ± 140 years.

Whereas the dated *Neotoma* middens record the presence of *Juniperus scopulorum, Pinus ponderosa*, and 13 other species at the time of deposition, the radiocarbon ages of the outermost sapwood of the logs pinpoint incidents of mortality in the juniper population. The available chronology of woodland conifers on the floor of the Laramie Basin, based on 18 radiocarbon dates scattered over a span of 5600 years, is summarized in Table 3. The record of *Juniperus* over the past 2300 years is based on 15 evenly dispersed radiocarbon dates; hence, there is no indication of catastrophic mortality of juniper during this time interval. Some clumping of juniper-sapwood dates would be expected if episodic drought-kill had occurred. As it is, the life-span of the larger junipers, indicated by ring counts on the logs, is much greater than the average interval between the radiocarbon dates, which is only about 150 years (Table 3). This implies a continuous existence of junipers on the floor of the basin during the last 2300 years. Nevertheless, the juniper population has now declined to the point of local extinction. The desiccated condition of the three surviving individuals of *Juniperus scopulorum*, their failure to reproduce, and their restriction to one site uniquely favored by runoff indicate that a trend to greater aridity has continued into the present century. The imminent demise of these individuals will bring to completion a gradual process of elimination of juniper from the floor of the southwestern corner of the Laramie Basin, an end point that evidently was not reached at any time during the past 2000 years or more.

A Post-Hypsithermal Maximum of Aridity in the Laramie Basin

The subfossil remains of *Juniperus scopulorum* and *Pinus ponderosa* from an arid part of the Laramie Basin document the occurrence of coniferous woodland at 16 different sites where none exists today. Since the record thus far obtained extends back some 5600 years, it follows that, at least in the latter part of the Hypsithermal interval of maximum postglacial warmth, it was significantly less arid here than it is today. According to Deevey and Flint (*20*), who proposed the term, the Hypsithermal interval extended from about 9000 to about 2500 years ago. It is broader in scope than the Altithermal interval of Antevs (*21*), which extended from 7500 to 4000 years ago. Relative to the European Blytt-Sernander sequence, the Hypsithermal corresponds in time to the Boreal, Atlantic, and Sub-Boreal zones, while the Altithermal is essentially equivalent in time to the Atlantic zone. The Sub-Boreal zone, now known to date from about 4500 to 2500 years ago, is thought to have been a time of maximal postglacial dryness, a European Xerothermic (*22*). The radiocarbon-dated record of woodland on the floor of the Laramie Basin during the last 5600 years spans the latter part of the Atlantic and all of the subsequent Sub-Boreal and Sub-Atlantic zones.

The common use in America of the term Xerothermic to describe a warm postglacial interval (*23*) implies that aridity was greater then than it is today. This interpretation is probably appropriate where precipitation is concentrated in the cool winter months and severe drought regularly coincides with the time of maximum evapotranspiration stress in summer, as in regions influenced by climatic rhythm of the Mediterranean type along the Pacific Coast and inland in the Mohave and Great Basin deserts. However, in the Rocky Mountains and Great Plains there is a profoundly different, monsoonal type of climatic regime, with a strong summer maximum of precipitation, from incursions of humid Gulf air, that tends to counteract the peak in evapotranspiration stress correlated with the summer maximum in temperature. The ecological differences between the two contrasting climatic rhythms should be enhanced by a general rise in summer temperatures. Hence, the interval of maximum postglacial warmth (the coinciding peaks of the "Hypsithermal," "Altithermal," or "Atlantic" intervals) should be expected to show different effects on climate and vegetation in regions that are fundamentally different today. Surprisingly, this basic point seems to have escaped proper emphasis. According to this view, there is no conflict or anomaly in the divergent indications of a rather moist Hypsithermal in the summer-rain area of southeastern Arizona (*24*) and a dry Hypsithermal in the summer-drought area of the Mohave Desert (*25*).

The available evidence points to a distinct possibility that the climate in the southwestern corner of the Laramie Basin may be more arid at present than it was at any time during the Hypsithermal interval of maximum postglacial warmth. In other words, the drastic shrinkage of woodland over the past several centuries, now culminating in a semidesert steppe on the floor of the basin, may constitute the first climatically induced interlude of treelessness at this locality in post-Wisconsin time.

Relevance to the Ecological History of the Great Plains

The indication of a climate significantly less arid than the present one during much of the latter half of postglacial time has major implications for the history of climate and potential vegetation on the Great Plains, only 48 kilometers east of the subfossil woodland sites. The edge of the Plains lies immediately to the east of the Front Range of the Rocky Mountains, the physiographic boundary on the east side of the Laramie Basin. Precipitation increases progressively toward the east on the Plains, despite a gradient of declining elevation in that direction. At the same latitude, the Great Plains province is decidedly less arid than parts of the Laramie Basin, where the existing vegetation bears a desertic stamp, as described above for the subfossil woodland locality in the southwestern corner. Correspondingly, a very significant feature of the existing vegetation of the Great Plains is the wide distribution of upland forests or woodlands in the vicinity of escarpments and other major topographic breaks. At the time of settlement, grasslands occupied most of the smooth topography—the flat or rolling plains and gentle slopes. Under the widest range of climate, nonriparian woodlands or forests coexisted on the uplands with grassland, but the forests were more or less restricted to rough, dissected topography associated with the bolder scarps, or to wind-swept mesas and buttes isolated by extensive grassy plains (*26*). Trees also occurred in relatively level upland sites on the leeward sides of lakes and rivers that afforded shelter from the wind-driven prairie fires (*27*), and the firebreak principle is equally applicable to the scarp woodlands (*26*).

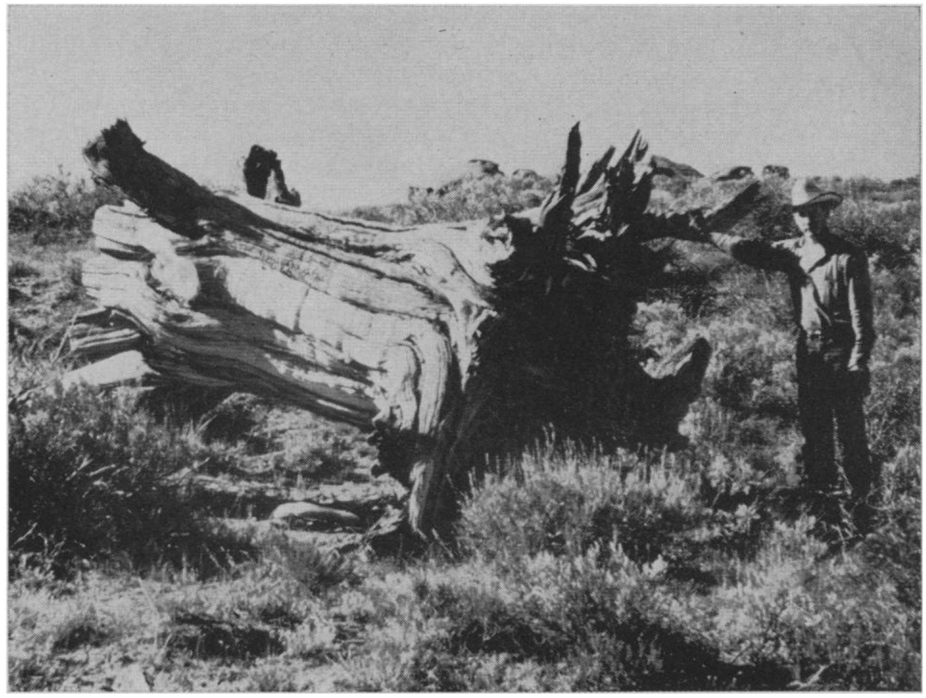

Fig. 2. Log of western red cedar (*Juniperus scopulorum*) with a trunk more than 1.3 meters in diameter, exposed at the surface of eolian sand deposits in the arid southwestern corner of the Laramie Basin, Wyoming. The age of the outermost sapwood, as determined by radiocarbon dating, is 940 ± 105 years, indicating the approximate time of death. A ring count on a 0.5-meter cross section at the apical end showed about 450 growth rings, suggesting that favorable climatic conditions prevailed on the floor of the basin during much of the first millennium A.D. The existing semidesert vegetation is dominated by the silver sagebrush (*Artemisia cana*).

Distribution of existing scarp woodlands in the Plains region. The zone of segregated coexistence of grassland and nonriparian, scarp-restricted woodland is not limited to a narrow ecotonal transition between regional forest and regional grassland. It extends across the entire width of the Central Plains in the latitude of the Prairie Peninsula, from Indiana through Illinois, Iowa, and Nebraska to Wyoming. In accordance with the east-west climatic gradient of decreasing precipitation and humidity, there is a shift from broad-leaf deciduous forest to open, xerophilous, coniferous woodland dominated by *Pinus ponderosa* Laws. and *Juniperus scopulorum* Sarg. along the scarps in central Nebraska. Similarly, the grasses on the adjacent plains decrease in height and density westward, as dominance shifts from the tall Andropogoneae in the east to the dwarf Chlorideae in the west. Nevertheless, the abrupt topographic segregation of woodland and grassland prevails throughout the gradient in vegetation and climate.

Even in the relatively dry western sector of the Plains, numerous wooded scarps interrupt the flat monotony of the short-grass steppe from eastern Montana south to New Mexico and Texas. For example, coniferous forests or open woodlands dominated by pines or junipers, with a lower synusia of grasses, occur in the midst of immense grasslands of arid aspect (because of their treelessness) at such topographic irregularities as Piney Buttes (eastern Montana); Pine Ridge escarpment (South Dakota, Nebraska, and Wyoming); Scott's Bluff and Wildcat Hills (western Nebraska); Pawnee Buttes, Cedar Point, and Two Buttes (eastern Colorado); Black Mesa (western Oklahoma); and Llano Estacado (New Mexico and Texas) (Fig. 1). These remarkable distributions of woodland throughout the Plains region create internal ecotonal boundaries between upland growths of woodland and grassland even in the most arid sectors of the Plains.

Well out on the Great Plains, along the westward-facing escarpment of the High Plains (the Ogallala formation) near Pine Bluffs in the southeastern corner of Wyoming, there are extensive woodlands dominated by *Pinus ponderosa* var. *scopulorum*, and, more remarkably, by limber pine (*P. flexilis* James), with western red cedar (*Juniperus scopulorum*), in exactly the same latitude as that of the subfossil woodland locality in the Laramie Basin but 130 kilometers to the east of it. The popular conception that the High Plains physiographic province is too arid for the growth of trees, except along streams, makes these upland occurrences of coniferous woodland seem anomalous. The idea that treelessness must be climatically induced is an extrapolation from observations in the more arid regions to the west of the High Plains, where the prevalent vegetation is a desertic shrub-steppe dominated by *Artemisia,* and where the trees—being obligately riparian, broadleaf, deciduous species of *Populus* and *Salix*—are indeed restricted to watercourses. In the desert, coniferous woodland is now lacking at the lower elevations, even along streams or on the boldest escarpments.

In fact, the ecological contrasts between the scarp woodlands and grasslands (or grass steppe) of the Great Plains and the treeless shrub-steppe vegetation of the semideserts or deserts to the west are readily explained by the long-term climatic records. The wooded Pine Bluffs locality on the grassy Plains has a distinctly wetter climate than the floor of the Laramie Basin, which lies just to the west of the Front Range of the Rocky Mountains and in its rain-shadow with respect to moist Gulf air masses. The mean annual precipitation at Pine Bluffs is 40 centimeters, as compared to 30 centimeters at Laramie, whereas the temperature regimes are quite similar (*28*). Since some species of juniper [*Juniperus scorpulorum* Sarg.; *J. monosperma* (Engelm.) Sarg.; and *J. pinchotii* Sudw.] inhabiting the scarp woodlands of the Plains also penetrate the margins of the winter-cold sagebrush deserts or the hot creosote-bush deserts, under climates more arid and fluctuating than those in any part of the Plains, it is indeed doubtful that the distribution of *treeless* grasslands is guided solely by "the master hand of climate," as Borchert assumed from circumstantial evidence (*29*). Circumstantial evidence also suggests that "the master hand" of physiography and other factors, including fire and climate, are involved.

The present wide distribution of scarp woodlands in the Plains, their recent increase (*30*), and a number of ancillary facts, such as the success of experimental tree plantations from North Dakota south to Texas (*31*), suggest an existing potential for a natural upland growth of various xerophytic tree species throughout much of the grassland province of North America. The potential must have been greater at times when the now much more arid southwestern corner of the Laramie Basin was wooded. The well-documented macrofossil record of the woodland conifers, *Juniperus scopulorum* and *Pinus ponderosa,* on the floor of the Laramie Basin at various times during the last 5600 years speaks for significantly more humid conditions, which should have had a counterpart on the less arid Great Plains, a short distance to the east.

A Neotoma *record of woodland on the Great Plains about 1500 years ago.* A rock-sheltered *Neotoma* midden, containing a woodland record with a radiocarbon age of 1530 ± 85 years (GX-1427) has recently been discovered in the Great Plains sector of southeastern Wyoming, about 50 kilometers east of the Front Range, southeast of Guernsey (Fig. 1). The deposit consists of abundant remains of woodland conifers, and it documents the presence of both *Juniperus scopulorum* and *Pinus ponderosa* on the Plains at a time when, according to other evidence, juniper woodland was present in the more arid Laramie Basin, about 150 kilometers to the southwest. On the other hand, the Guernsey *Neotoma* site is in the midst of a scarp woodland of *Juniperus scopulorum* and *Pinus ponderosa* today, and the scarp bounds an extensive grassy plain. The record does contribute to the history of the scarp woodland, showing that the existing conifers were in the Great Plains about 1500 years ago, but it offers no information on treeless grassland. However, then as now, the potential for spread of xerophytic tree species, well-adapted to upland growth on the Plains, may have been realized only close to seed sources that had been sheltered from prairie fires, perhaps for thousands of years, by abrupt breaks in topography.

The interaction of topography and fire in the origin and maintenance of grasslands. For the well-entrenched point of view that the distribution of treeless grasslands is governed principally by climate (*32*), the wide distribution of scarp woodlands throughout the climatically diverse grassland province poses some difficult questions. Regardless of local or regional variations in climate and regardless of the species composition of both woodland and grassland in the Plains region, the following relation holds: the rougher and the more dissected the topography, the greater the former extent and the current spread of woody vegetation at the expense of grassland (*26*). Over and above the droughty climate, which undoubtedly has been a contributing factor, it is the vast flat or rolling smoothness and continuity of surface of the relatively undissected sedimentary mantle that appears to have played a powerful role in the development of the great expanses of treeless grassland on the Plains. The topographic control of vegetation pattern implied by the distribution of extensive grassy plains and scarp-restricted woodlands in the Central Plains region can be explained as a resultant of many interacting factors. However, wind-driven grass fires, whether ignited by lightning or by man, must be accorded a key position in the hierarchy. The wavelike motion of a wind-swept grass fire across a flat or rolling plain would continue indefinitely until it was quenched by rain or checked by an abrupt break in topography. A bold, rocky, sparsely grassed escarpment would serve as a natural firebreak, harboring fire-sensitive trees in safe sites, as on rocky promontories, and in the rincons or reentrants. From these seed sources, a slow lateral encroachment on the adjacent grassy plains could proceed, as is now occurring (*30*). The scarp woodlands of the Plains may be viewed as insular relicts of woody vegetation in a formerly fire-swept sea of grass.

The seasonally dry perennial grasses serve as a highly flammable fuel that may burn with sufficient heat to injure or kill woody plants, but a new crop of grass is regenerated from protected buds after each fire. The establishment of seedlings of xerophytic tree species in grassland is hazardous under the droughty climate of the Central Plains, even with protection from fire, and successful reproduction is usually limited to the relatively rare sequences of wetter years. But the pattern of recurrent fire prevalent in "natural" grasslands is disastrous to seedlings or saplings of trees during the many precarious years of vegetative growth required to attain seed-bearing maturity. Fire is particularly disastrous to conifers that lack the capacity to sprout from older wood or stumps following destruction of the resinous tops.

These relations would have held with equal or greater force for the late-Wisconsin boreal spruce flats of the northern Plains, when they began to suffer from the effects of postglacial warming of climate. A *coup de grâce* from forest fire is a likely fate for nonsprouting boreal conifers stranded under an unfavorable climate. An elegant analogue is the presence of charcoal horizons, with radiocarbon ages ranging from 900 to 3500 years, over forest podzols in the Keewatin tundra, as much as 280 kilometers north of the present tree line (*33*). Advances of the boreal forest into the tundra during periods of milder climate (the older dates correspond to the latter part of the Hypsithermal interval) were followed by catastrophic forest fires and a failure of forest regeneration under periods of adverse climate (the latest being the last 900 years).

Although the modern vegetation pattern on the Plains has had all of postglacial time in which to develop (potentially, 8000 to 10,000 years), an early elimination of boreal conifers and scarp-restriction of temperate tree species would be expected, as indeed the pollen record from the northern Plains indicates (*4–6*). A catastrophic elimination of the highly combustible and ill-adapted spruce forests would have opened a vast expanse of northern plains to the rapid spread of mobile, opportunistic plants, such as herbaceous Compositae and Gramineae and the wind-dispersed aspen (*Populus tremuloides* Michx.) that sprouts after fire and proliferates laterally from the roots. The sheer extent of deforested plains or aspen parklands (to the north) would insure a long hiatus of open vegetation because migration of potentially adapted, xerophytic, temperate tree species from distant refugia into the central sectors of the Plains must have required a great deal of time, under even the most favorable climatic conditions. The migration of trees is slowed by the relatively long interval of maturation, often as much as 10 to 20 or more years between dispersals. Mass migration of tree species, and hence of forest, would proceed at a much slower rate than isolated colonizations due to occasional long dispersals. The recurrent fire and drought on the wind-swept plains would be sufficient to delay indefinitely the centripetal migration of trees from peripheral, sheltered sites.

Hence, it seems reasonable to suppose that scarp-restriction of forest or woodland vegetation throughout the region of grassy plains in the central part of the continent *originated* as a consequence of regional forest and prairie fires, and that subsequent annual conflagrations helped to maintain a treeless condition by sweeping the seasonally dry grasslands on the smooth surface of the Plains for great distances, until the fires were stopped by an abrupt topographic break. When all the facts are admitted, the generalization that the treeless grasslands of the Great Plains are climatically determined seems simplistic. Obviously, climate is a factor, as is always true in plant geography, but there are others: the regional flatness and continuity of the physiography; the smooth, relatively undissected mantle of unconsolidated Pleistocene sediments; the fuel-producing, annual dieback of grasses characteristic of the herbaceous way of life; and the *sine qua non,* fire.

Summary

Radiocarbon-dated macrofossil and pollen records from the Plains region of central North America indicate that areas now occupied by grassland or desert vegetation were wooded during the Wisconsin glacial. In the northern part of the Great Plains, boreal conifers characteristic of the existing Canadian taiga occurred at widely scattered localities from southern Saskatchewan south to Kansas and from Minnesota south to Missouri. On the warmer and more arid Plains of the Llano Estacado in the southern part of the Texas panhandle, several pollen profiles from Wisconsin-age sediments show very high contents of pine pollen (more than 90 percent) and low contents of spruce pollen (10 percent or less). Abundant macrofossil evidence has been obtained at the southwestern border of the Plains. In what is now one of the most arid sectors of the Chihuahuan Desert, an open, xerophilous woodland of piñon pine (*Pinus cembroides* var. *remota*), live oaks, and juniper prevailed during Wisconsin time. But there is no indication that *treeless grassland* shifted southward into what is now the arid Chihuahuan Desert during the Wisconsin glacial, when much of the Great Plains south of the ice sheet was occupied by coniferous forest, woodland, or possibly parkland.

At most of the fossil pollen sites in the Plains region there is a dramatic decrease in coniferous pollens in the postglacial sediments. This is usually interpreted as a climatically induced shift to more xerophytic, nonarboreal vegetation similar to the prairies of today. However, there is a remarkable record of coniferous woodland during the latter half of postglacial time on the now arid floor of the Laramie Basin in southeastern Wyoming. The record consists of plant macrofossils ranging in size from massive logs of western red cedar (*Juniperus scopulorum*), exposed at the surface or partly buried in eolian sand deposits, to leaves, cones, and seeds of juniper and ponderosa pine (*Pinus ponderosa* var. *scopulorum*) preserved in rock-sheltered wood-rat middens. On the basis of 18 radiocarbon dates, the record of woodland extends from about 5600 years ago to a remarkably recent 205 ± 95 years ago. Hence, a climate significantly less arid than today's is indicated for a time span that encompasses the latter half of the Hypsithermal interval of maximum postglacial warmth. Also reported is a *Neotoma* midden containing a woodland record with a radiocarbon age of about 1500 years, in the Great Plains sector of Wyoming.

The presence of woodland on the now arid floor of the southwestern corner of the Laramie Basin during much of the latter half of postglacial time has major implications for the history of climate and potential vegetation on the Great Plains, only 48 kilometers to the east. At the same latitude, the Plains are now decidedly less arid than parts of the Laramie Basin, and precipitation increases progressively toward the east. Correspondingly, a significant feature of the existing vegetation of the Great Plains is the wide distribution of upland, nonriparian forests and woodlands in the vicinity of escarpments and other major topographic breaks. At the time of settlement, grasslands occupied most of the smooth topography—the flat or rolling plains and gentle slopes.

A rational explanation of these phenomena is that scarp-restriction of forest or woodland vegetation throughout the region of grassy plains in the central part of the continent originated as a consequence of regional forest and prairie fires. Climate is a factor, but so are the regional flatness and continuity of the physiography, the fuel-producing, annual dieback of grasses characteristic of the herbaceous way of life, and fire.

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19. Also present on the plains are the grasses *Stipa comata* Trin. & Rupr., *Agropyron smithii* Rydb., and *Koeleria cristata* (L.) Pers., an arid-land sedge (*Carex filifolia* Nutt.), and the prickly pear (*Opuntia polyacantha* Haw.). Also on the sands are rabbit brush [*Chrysothamnus viscidiflorus* (Hook.) Nutt.], *Yucca glauca* Nutt., Indian rice grass [*Oryzopsis hymenoides* (R. & S.) Ricker], antelope brush [*Purshia tridentata* (Pursh) DC.], horse brush (*Tetradymia canescens* DC.), four-wing saltbush [*Atriplex canescens* (Pursh) Nutt.], and winter-fat [*Eurotia lanata* (Pursh) Moq.]. The low ridges of sandstone at the site are sparsely vegetated with somewhat less xerophytic deciduous shrubs, principally mountain mahogany (*Cercocarpus montanus* Raf.) and squaw bush (*Rhus trilobata* Nutt.), with service berry (*Amelanchier utahensis* Koehne), and with wax currant (*Ribes cereum* Dougl.).
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Advances in Computer-based Education

The Plato program will provide a major test of the educational and economic feasibility of this medium.

D. Alpert and D. L. Bitzer

Since its initiation in 1959, the PLATO program (*1*) at the University of Illinois has been committed to exploration of the educational possibilities and the engineering and economic problems relating to the introduction of the modern high-speed computer as an active element in the instructional process. During the past decade, numerous other groups at universities, nonprofit institutes, and industrial corporations have also begun to explore the possibility of utilizing modern computer technology for education. A widely varying array of such efforts is encompassed by the term "computer-assisted instruction" (CAI).

The setting for these activities is an overall formal educational process in which the national investment is more than $50 billion annually, a commitment which is expected to increase to well over $100 billion by 1980. Yet, despite this large national commitment, it is commonly agreed that there are vast unmet needs in education, in terms both of quantity and of quality. There are growing demands for more mass education over a larger fraction of the human life-span, and demands for more individualized instruction tailored to the specific preparation and motivation of a given student. However, these expanding educational needs have not been matched by increases in the productivity of the educational process. Rather, the costs per student at all levels and in various types of institutions have been rising so rapidly as to cause serious concern for the future (*2*).

Under these circumstances, it is not surprising that many institutions have sought to enhance educational productivity and to enrich the instructional process by the introduction of technology, especially the technology of the modern high-speed computer. The many programs in computer-assisted instruction have been based on recognition of the unique value of the computer in adapting the selection and presentation of instructional materials to the pace and style of individual students and in acquiring and processing data relating to the effectiveness of the teaching and learning processes. Nevertheless, although some of these programs have met with great enthusiasm on the part of highly qualified educators, it is fair to say that the general reaction has been mixed.

The mixed impressions about computer-assisted instruction are due in part to the wide variation in notions as to the types of systems that are feasible and the teaching strategies that are possible. Several recent assessments of the field (*3*) attest to the wide diversity of the objectives and professional specialization of such programs and to the even greater diversity of technological and educational resources available to them. At one end of the spectrum is the conception of such instruction simply as an automated version of a drill and practice lesson or a pro-

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