Climatic and edaphic conditions at *Eragrostis lehmanniana* Nees sites in Arizona, USA and the Cape Province, RSA and potential seeding sites in southern Africa

Jerry R. Cox
U.S. Department of Agriculture, Agricultural Research Service, 2000 E. Allen Road, Tucson, Arizona 85719, USA

J.L. Stroehlein
University of Arizona, Soil and Water Department, Tucson, Arizona 85721, USA

J.H. Fourie
Sentraalwes Agricultural Centre, P.O. Box 677, Bloemfontein 9300, Republic of South Africa

Accepted 26 November 1989

Climatic and edaphic conditions at *Eragrostis lehmanniana* Nees sites in southeastern Arizona, USA were compared with those in the Cape Province, RSA to determine a range of conditions under which the species might be expected to establish and persist in southern Africa. Mean annual precipitation amounts and temperature extremes were highly variable where Lehmann lovegrass predominates, but in most summers precipitation accumulations ranged from 150–220 mm and temperature extremes ranged from 20–35°C in 30–40 days. Soils at Lehmann lovegrass sites in the Cape Province were more coarse textured and nutrient concentrations were usually less than at sites in southeastern Arizona; but trends in particle-size distributions and measured chemical concentrations were generally equivalent. Climatic and edaphic conditions in central Botswana and northeastern Namibia generally range between those in southeastern Arizona and the Cape Province, RSA and we expect that seeded Lehmann lovegrass stands in these areas would enhance semi-desert grassland productivity.

Edafiese en klimaatstoestande is gemeet op plekke in die suidelike dele van Arizona (VSA) waar *Eragrostis lehmanniana* Nees voorgekom het. Dit is vergelyk met dié in die Kaapprovinsie (RSA) om 'n reeks van toestande te bepaal waar dit verwag word dat die spesie sal vestig en sal oorleef in Suider-Afrika. Die gemiddelde neerslag en die uiterstes in temperatuur was hoogs verskillend waar knietjiesgras voorgekom het. Die somerneerslae het gevarieer van 150–220 mm en die temperatuuruiterstes het gewissel van 20–35°C in 30–40 dae. In die Kaapprovinsie het die grond by die plekke met knietjiesgras, 'n meer growwe tekstuur gehad en die voedingstofkonsentrasies was oor die algemeen laer as by die plekke in suidelike Arizona. Die neiging in die partikelgrootte se verspreiding en die chemiese konsentrasies was oor die algemeen dieselfde. Edafiese en klimaatstoestande in sentraal-Botswana en noordelike Namibië is gewoonlik tussen dié van suidelike Arizona en die Kaapprovinsie. Daar word dus verwag dat gesaaide knietjiesgrasstande in hierdie dele die produksie van die semi-woestyngrasveld sal verbeter.

Additional index words: Northern and Southern hemispheres, Sonoran and Kalahari deserts, climatic and edaphic comparisons

Introduction

Lehmann lovegrass (*Eragrostis lehmanniana* Nees), a perennial warm-season bunchgrass is native to and widely distributed in central South Africa (Acocks, 1975). The species predominates where surface soils are sandy and annual precipitation varies from 250–500 mm (Fourie & Roberts, 1976).

Lehmann lovegrass seed collected in Griqualand, Cape Province was sown and evaluated for seedling establishment during 1932 at Superior, Arizona, USA (Crider, 1945). Seedlings, from seed sown in summer, matured quickly and in the first growing season produced viable seed. In 1937 the USDA-Soil Conservation Service initiated a seed production program and by 1960 Lehmann lovegrass seed had been sown in Arizona, New Mexico, west Texas and in the northern Mexico frontier states of Chihuahua, Coahiula and Sonora (Cox *et al.*, 1982).

Lehmann lovegrass was initially established at most planting sites and land managers assumed that the species would persist under a wide variety of climatic and edaphic conditions (Cable, 1976). Established populations, however, spread only in southeastern Arizona, whereas, populations outside Arizona have either persisted but not spread or disappeared (Cox & Ruyle, 1986).

In southern Africa, semi-desert grassland productivity declines with over-grazing and shrub densities increase (Fourie & Roberts, 1976). If African semi-desert grassland productivity is to be increased it may be necessary to either chemically or mechanically reduce shrub competition and seed a perennial grass, such as Lehmann lovegrass (Cox *et al.*, 1986). Because Lehmann lovegrass occurs naturally in southern African ecosystems, land managers may assume that the species can be easily established and will persist under a wide variety of climatic and edaphic conditions. Such assumptions, as previously shown, may be incorrect.

Since Lehmann lovegrass is self-perpetuating in two widely-spaced continents, we believe that climatic and edaphic conditions where the species spreads in Arizona are similar to those where the species occurs most frequently in central South Africa. If this hypothesis is true, the results of this study and others conducted in North America and South Africa can be used to select potential Lehmann lovegrass seeding sites in southern Africa.

Procedure

Study sites

Twelve Lehmann lovegrass communities were selected subjectively in Arizona (USA) and the Cape Province (RSA). Arizona sites were near the settlements of: (1) Oracle, (2) Pearce, (3) Portal, (4) Santa Rita, (5) Sasabe, and (6) Sierra Vista (Figure 1). The Cape Province sites were near the settlements of: (7) Armoedsvlakte, (8) Jan Kempdorp, (9) Kimberley, (10) Koopmansfontein, (11) Kuruman, and (12) Vryburg.

Lehmann lovegrass was the predominant perennial grass at the twelve sites but densities were greatest in Arizona where the grass occurs in monocultures. The grass shares co-dominance with mesquite (*Prosopis juliflora* (SW.)DC.) in Arizona and *Acacia* spp. in the Cape Province.

Elevations vary from 1 105–1 435 m in Arizona and from 1 150–1 340 m in the Cape Province. Slopes range from 4–10% in Arizona and from 1–2% in the Cape Province. In Arizona annual precipitation ranges from 295–505 mm, and approximately 60% is distributed in summer and 40% in winter (Sellers & Hill, 1974). In the Cape Province annual precipitation ranges from 425–475 mm, and approximately 90% is distributed between spring and autumn (Weather Observational Network: Station Register, 1985).

Weather parameters

Weather categories were (1) precipitation and, (2) maximum and (3) minimum temperatures. Site parameters were summed by months and divided by record lengths. Precipitation and temperature records were measured at each site for more than 20 years. Seasons in Arizona and the Cape Province are offset by approximately 6 months, therefore, monthly weather parameters were adjusted so that winter, spring, summer and fall seasons were the same at the twelve sites.

Soil sampling

Three typical Lehmann lovegrass plants of approximately the same height and canopy area were selected at each site. Soils were collected near the crown of each plant at: (1) 0–5, (2) 5–10, (3) 10–15, (4) 15–25, (5) 25–35 and (6) 35–45-cm depths. Soils were air-dried, passed through a 2-mm sieve and thoroughly mixed.

Soil analyses

A sub-sample from each soil sample was analysed for

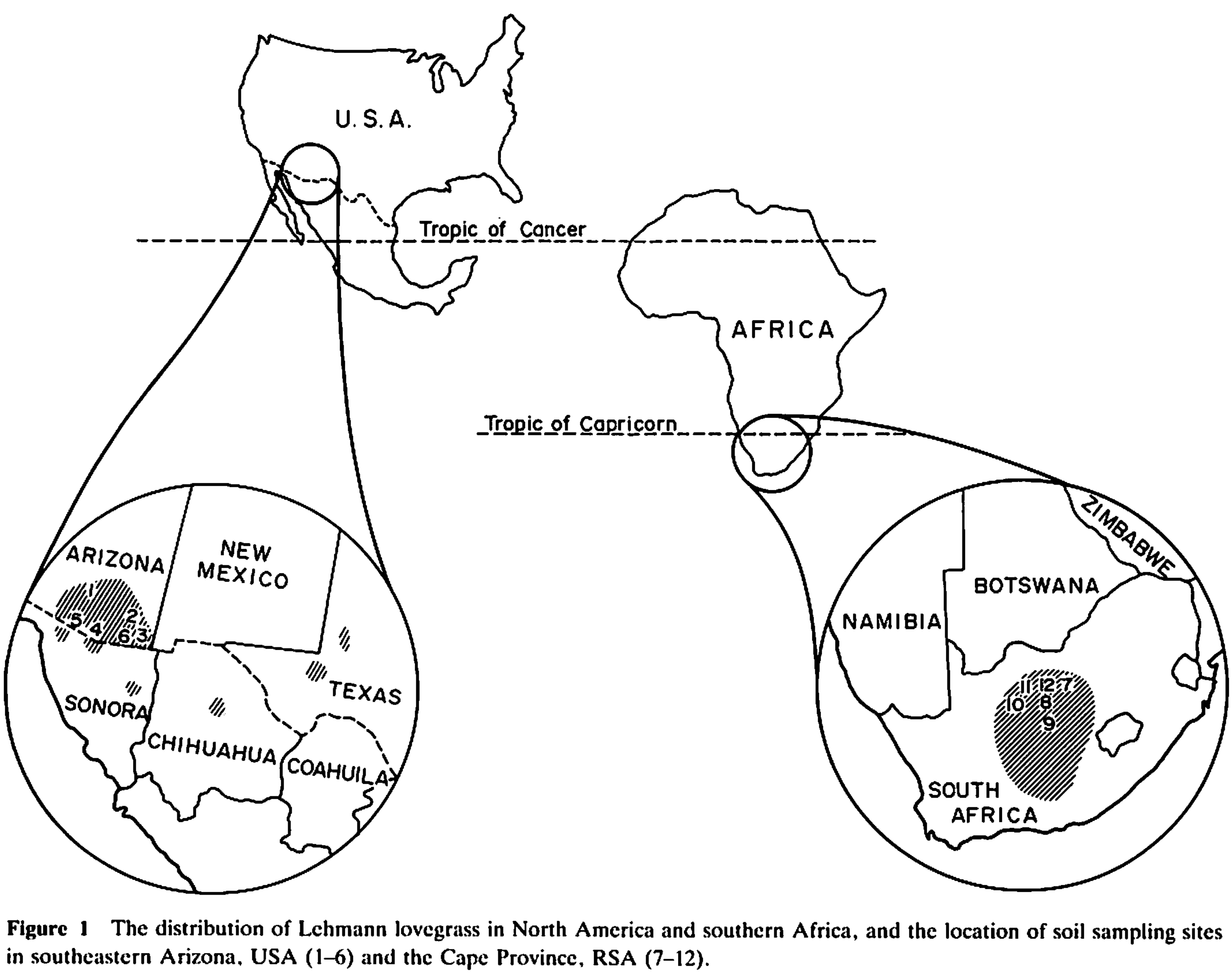

Figure 1 The distribution of Lehmann lovegrass in North America and southern Africa, and the location of soil sampling sites in southeastern Arizona, USA (1–6) and the Cape Province, RSA (7–12).

particle-size distribution (Day, 1950), pH (saturated paste), electrical conductivity (EC) of the saturation extract (U.S. Salinity Laboratory Staff, 1954), ammonium acetate soluble cations including calcium (Ca), potassium (K), sodium (Na) and magnesium (Mg), organic carbon (Jackson, 1958) and available phosphorus (P) (Olsen & Sommers, 1982).

Experimental design

The data were analysed with a hierarchical design that included locations (Arizona and Cape Province), sites and soil depths. The three sampling areas at a site were considered as nested replications because they represented the expected variability among sites within a location. An analysis of variance was performed for each soil component. The error mean squares, however, could not be used in the F-tests because the site within location and the depth by site within location mean squares were greater than the error mean squares. Therefore, the site within location mean square was used to test for differences between locations while the depth by site within location mean square was used to test for differences among soil depths and the depth by location interaction.

Results and Discussion

Weather parameters

Total mean annual precipitation at the six Cape Province sites ($\bar{x}$=450 mm) is approximately 12% greater than the six Arizona sites ($\bar{x}$=400 mm). Precipitation is distributed in spring, summer and fall (September–April) and winters are dry at the Cape Province sites while precipitation is distributed in summer and winter, and spring and fall are usually dry at the Arizona sites (Figure 2). Mean annual minimum and maximum temperatures range from 9,3–26,3°C and 8,8–24,8°C at the Cape Province and Arizona sites, respectively. Spring and winter temperatures are warmer at the Cape Province sites while summer and fall temperatures are warmer at the Arizona sites (Figures 3 & 4).

Precipitation amounts and temperature extremes are highly variable between locations and among sites, but climatic conditions are similar for 4–6 weeks in 16 of the

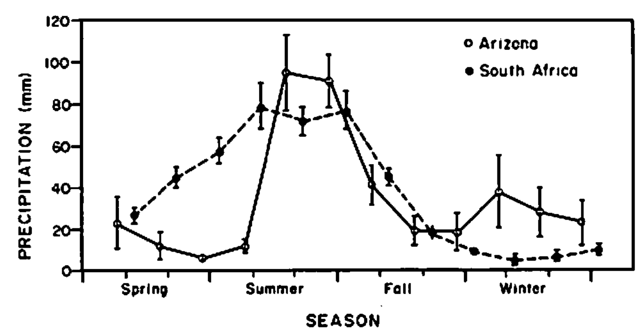

Figure 2 The variation in mean monthly precipitation distribution at six sites in southeastern Arizona, USA and six sites in the Cape Province, RSA.

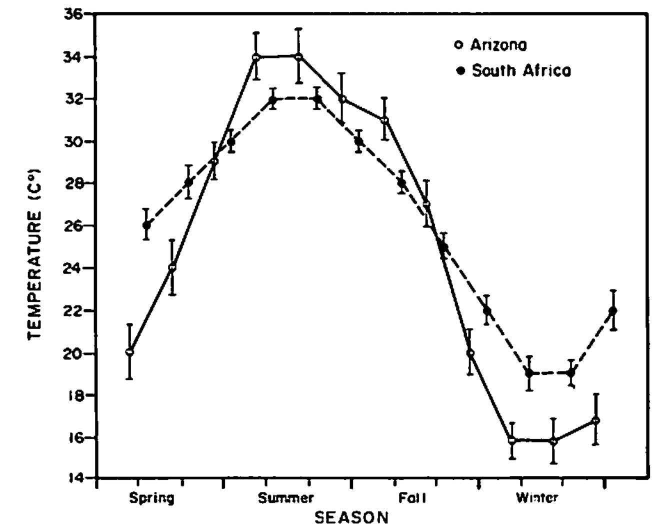

Figure 3 The variation in mean monthly maximum temperatures at six sites in southeastern Arizona, USA and six sites in the Cape Province, RSA.

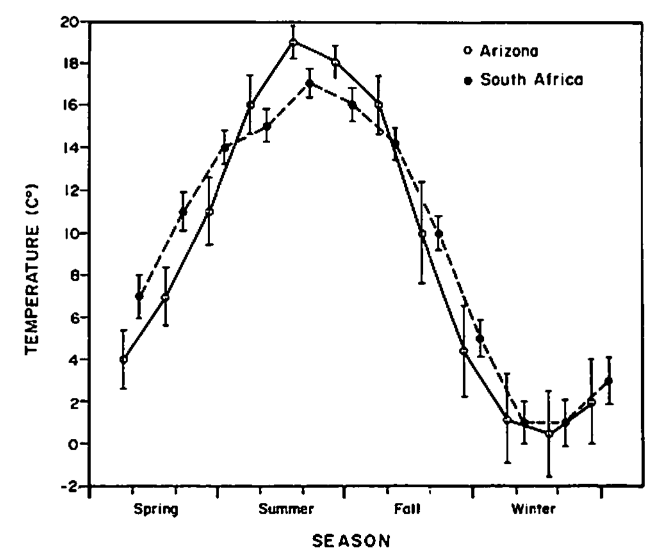

Figure 4 The variation in mean monthly minimum temperatures at six sites in southeastern Arizona, USA and six sites in the Cape Province, RSA.

20 years (Sellers & Hill, 1974; Weather Observational Network: Station Register, 1985). In 30–40 days, during summer at the Cape Province sites (November–February) or during late summer at the Arizona sites (July–August) precipitation accumulations range from 150–200 mm, temperature extremes range from 20–35°C and relative humidity ranges from 45–85%.

When summer precipitation ranges from 150–220 mm, thunderstorms at both the Cape Province and Arizona sites usually occur at 1–4-day intervals (Agroclimatological data for Africa: Countries south of the equator, 1984; Climatography of the Unites States, 1982). Under these conditions Lehmann lovegrass seed germinates in 4–5 days (Cox, 1984), seedlings emerge in 9–12 days and seedlings produce viable seed in 30–40 days (Crider, 1945). When summer precipitation is less than 150 mm, thunderstorm activity is irregular and Lehmann lovegrass seedlings die (Frasier *et al.*, 1985), but ungerminated seed retains viability and germinates when soil moisture conditions improve (Fourie & Roberts, 1976; Ruyle *et al.*, 1988).

Spring precipitation amounts at the Cape Province sites are 3,6 times greater than those at the Arizona sites, winter amounts at the Arizona sites are 4,0 times greater than those at the Cape Province sites and fall amounts are about the same at both locations (Sellers & Hill, 1974; Weather Observational Network: Station Register, 1985). Night-time temperatures are frequently below 15°C at both locations in the fall, winter and spring. Lehmann lovegrass seed do not germinate and above-ground growth is limited when temperatures are below 15°C (Cox, 1984), but in the Cape Province growth occurs in late spring when moisture is available in the soil (Fourie & Roberts, 1976). In Arizona winter moisture evaporates or moves below the rooting zone before spring night-time temperatures approach 15°C (Cable, 1977).

Soil physical and chemical properties

Soils were generally coarse-textured and non-saline at the twelve sites, but the Cape Province soils were more coarse and generally had lower P, Na, K, Ca and Mg concentrations (Tables 1, 2 & 3). Soil physical and chemical differences are attributed to the type and age of soil parent material.

In Arizona, Lehmann lovegrass stands were found on alluvial fans beneath granitic mountain peaks (Hendricks, 1985). At these sites, geologically young acidic granitic soils developing at high elevations (2 600–3 200 m) were deposited by water over geologically old alkaline sedimentary soils at lower elevations (900–1 500 m). Geologically young granitic soils are high in Ca, Mg and P, and are slightly acid because they have undergone little leaching and weathering (Hausenbuiller, 1978).

Table 1 Particle-size distribution and selected chemical properties within Lehmann lovegrass communities in Arizona, USA and the Cape Province, RSA. Presented values are averages from six soil depths at six sites and they are presented in this format because the location by depth interactions were not significant

Property	Locations		F-test
	Arizona	Cape Province	
Sand (%)	67,6	79,1	*
Silt (%)	16,3	10,7	NS
Clay (%)	16,1	9,2	*
pH	6,0	7,1	*
EC (ds/m)	0,2	0,1	NS
Organic C (%)	0,4	0,4	NS
P (mg/kg)	6,5	2,9	**

* Significant at 95% level of probability
** Significant at 99% level of probability
NS = Not significant

Table 2 Particle-size distribution and selected chemical properties of six soil depths at twelve Lehmann lovegrass sites in Arizona, USA and the Cape Province, RSA. The presented values are averages from 12 sites and are presented in this format because the location by depth interactions were not significant

Property	Depth (cm)						F-test
	0–5	5–10	10–15	15–25	25–35	35–45	
Sand (%)	77,5	75,8	73,2	72,3	70,7	70,5	**
Silt (%)	13,0	13,0	13,6	13,7	13,9	13,8	NS
Clay (%)	9,5	11,2	13,2	14,0	15,4	15,7	**
pH	6,3	6,4	6,5	6,7	6,8	6,8	*
EC (ds/m)	0,2	0,2	0,1	0,1	0,1	0,1	NS
Organic C (%)	0,6	0,5	0,4	0,4	0,3	0,3	*
P (mg/kg)	7,9	5,6	4,4	3,7	3,2	3,3	**

* Significant at 95% level of probability
** Significant at 99% level of probability
NS = Not significant

In the Cape Province, soils are deep, wind-deposited sand (Mac Vicar *et al.*, 1977) from ancient sedimentary Gondwanaland formations in southwestern Africa (Sanders *et al.*, 1976). In geologically old soils, Ca and Mg are leached from surface soil exchange sites and replaced by H and Al; and in time pH declines. The Cape Province soils have probably remained neutral because precipitation is not adequate to move Ca and Mg below the rooting zone (Brady, 1974).

Cape Province soils are more coarse and in our opinion less fertile than Arizona soils but particle-size distribution and nutrient concentration trends in the solum are generally equivalent at both locations (Tables 2 & 3). At all sites sand declines with profile depth and available P and organic C are concentrated near the soil surface where root activity is greatest. Argillic or fine sand horizons, or caliche ($CaCO_3$) or dolomite ($Mg(CO_3)_2$) barriers are located at 30–90-cm depths (Hendricks, 1985; Mac Vicar *et al.*, 1977).

Potential Lehmann lovegrass seeding sites in southern Africa

The Lehmann lovegrass distribution centre is located in central South Africa (Acocks, 1975), but the distribution area might be moved north if it was desirable to improve semi-arid grassland productivity. Summer precipitation amounts on the western boundary of the shaded area (Figure 5) exceed or equal 150 mm in 2 or 3 of 10 years; while amounts within the shaded area exceed or equal 150 mm in 7 or 8 of 10 years (Agroclimatological data for Africa: Countries south of the equator, 1984; Weather Observational Network: Station Register,

Table 3 Selected chemical properties of soils at six depths within Lehmann lovegrass communities in Arizona, USA and the Cape Province, RSA. The presented values are averages from six sites and are present in this format because the location by depth interactions were significant

		Depth (cm)					
Property	Location	0–5	5–10	10–15	15–25	25–35	35–45
Na (cmol/kg)	Arizona	0,5a*	0,5a	0,6a	0,3b	0,3b	0,5a
	Cape Province	0,3b	0,1c	0,1c	0,0c	0,0c	0,0c
K (cmol/kg)	Arizona	4,4a	4,2ab	4,0ab	3,6ab	3,3b	3,2b
	Cape Province	1,5c	0,5d	0,4d	0,4d	0,3d	0,2d
Ca (cmol/kg)	Arizona	19,9c	23,4d	31,1ab	32,9a	30,8a	27,0c
	Cape Province	4,8g	5,0fg	5,2fg	6,0fg	6,8f	5,5fg
Mg (cmol/kg)	Arizona	8,7cd	10,6c	12,0bc	13,4ab	14,3a	15,3a
	Cape Province	1,5f	1,5f	1,5f	2,7ef	3,6e	3,6e

* Means within the same property followed by the same letter are not significantly different at the 95% level of probability

1985; Wernstedt, 1972). In the USA, summer precipitation amounts in west Texas and southeastern New Mexico are similar to those on the western boundary, while amounts in southeastern Arizona are similar to those within the shaded area (Climatography of the United States, 1982). In west Texas and southern New Mexico, Lehmann lovegrass can be established in atypically wet summers but mature plants die in 3–5 years (Cox *et al.*, 1982). In southeastern Arizona, on the other hand, the species can be established in most summers and spreads in atypically wet summers (Cable, 1976). Spring, summer and fall precipitation amounts usually exceed 500 mm on the eastern boundary of the shaded area, and in northern Texas and Oklahoma, USA (Cox *et al.*, 1988). Lehmann lovegrass can be established at high precipitation sites in the USA, but long-term persistence is limited by competition with more productive forbs and grasses (Crider, 1945).

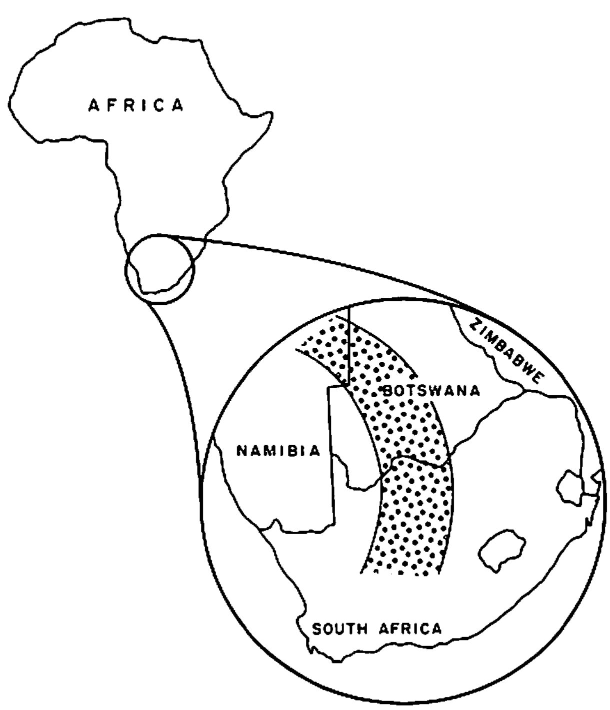

Figure 5 The area in southern Africa (shaded) where Lehmann lovegrass could potentially be used to enhance semi-desert grassland productivity. Climatic and edaphic conditions in the shaded area are similar to those at Lehmann lovegrass sites in southeastern Arizona, USA and the Cape Province, RSA.

Lehmann lovegrass seed sown in moist sand, sandy loam, silt and clay surface soils germinate within 72 hours, but seedlings emerge only from sand and sandy loam soils (Cox, 1984). In Figure 5, sand and sandy loam soils predominate throughout the shaded area (Mac Vicar *et al.*, 1977; Soil Map of the World – Africa, 1977; Van der Merwe, 1962) and we would expect Lehmann lovegrass seedlings to emerge, except in the southeast (Karoo region) where silt loam and clay loam surface soils are common.

During dry summers, mature Lehmann lovegrass plants die when rooted in deep sand (Jordan, 1981) or in shallow sand underlain by caliche and dolomite (Fourie & Roberts, 1976), but plants persist in sand or sandy loam surface soils underlain by restrictive horizons at 30–90-cm depths (Cable, 1976). On the western boundary of the shaded area soils are deep sand (Mac Vicar *et al.*, 1977; Soil Map of the World – Africa, 1977). In this area we would not expect mature Lehmann lovegrass plants to persist because restrictive soil horizons are usually at great distances beneath the soil surface and soil moisture moves rapidly through the solum (Van der Merwe, 1962). In localized areas within the southern portion of the shaded area, restrictive horizons occur near the soil surface (10–15 cm). At these locations, the solum dries quickly and mature plants would not be expected to persist during dry summers.

Conclusions

Attempts to artificially revegetate degraded rangelands in the northern and southern hemispheres have been ongoing for 100 years (Cox *et al.*, 1982; Humphreys, 1967). The method most widely used to establish perennial grasses was to: (1) either chemically or mechanically reduce shrub competition, (2) prepare a seedbed, (3) plant seeds of as many species, accessions and cultivars in as many soil textural types as possible, and (4) pray for rain (Cox *et al.*, 1988). Under these conditions grasses were successfully established in 1 out of every 10 planting attempts, but climatic and edaphic data were not collected at sites where seedings were successes or failures and it was impossible to predict why plants persisted or died.

In the 1970's, world petroleum costs increased dramatically and a successful seeding in 1 out of every 10 attempts was no longer a worthwhile investment. If range seeding is to become a viable economic endeavour in the 1990's the probability of success must be improved. Thus, information which defines the relationships among climate and soils, and plant germination, emergence, persistence and reproduction is essential.

In central Botswana and northeastern Namibia soil chemical and physical properties and late summer climatic conditions generally range between those measured at Lehmann lovegrass sites in southeastern Arizona and the Cape Province. Because climatic and edaphic conditions are highly variable within the shaded area in Figure 5 we cannot conclusively state that Lehmann lovegrass is adapted at all potential planting sites. However, this study and others (Cable, 1976; Cox *et al.*, 1986; Ruyle *et al.*, 1988) suggest that Lehmann lovegrass seedlings will colonize sand or sandy loam surface soils if shrub competition is reduced, while long-term persistence depends on soil horizons or rock layers (30–90-cm depth) that slow the downward movement of soil moisture.

Acknowledgements

Appreciation is extended to former South African Agricultural Counsellors P. F. du Toit and J. Boyazoglu of the South African Embassy in the U.S.A., the Grassland Society of southern Africa, farmers Gilbert and Sandy Speedy (Vryburg), Flip van den Berg (Verleë), Gert and Johan Olivier (Kuruman) and Okker Oosthuizen and A. D. Mills (Steynsburg) for their time and hospitality, Chris Biel (Armoedsvlakte Research Station) for soil collections, Drs. D. M. Scotney (Soil and Irrigation Research Institute) and D. Grossman (Grassland Research Centre) for providing soil laboratory staff, and Mrs Hattingh and Miss Pretorius for their administrative assistance.

References

Acocks, J.P H., 1975. Veld types of South Africa, 2nd edition. *Mem. Bot. Surv. S. Afr.*, No. 40. Pretoria: Govt. Printer.

Agroclimatological Data for Africa: Countries south of the equator, 1984. *Food and agriculture organization (FAO) of the United Nations*. Rome, Italy: Tipolitografia F. Failli.

Brady, N.C., 1974. *The nature and properties of soils*, 8th edition. New York: MacMillan Publishing Co.

Cable, D.R., 1976. Twenty years of changes in grass production following mesquite control and reseeding. *J. Range Mgmt.*, **29:** 286–289.

Cable, D.R., 1977. Seasonal use of soil water by mature velvet mesquite. *J. Range Mgmt.*, **30:** 4–11.

Climatography of the United States, 1982. *National Oceanic and Atmospheric Administration*. Ashville, NC (USA): Govt. Printer.

Cox, J.R., 1984. Temperature, timing of precipitation and soil texture effects on germination, emergence and seedling survival of South African lovegrasses. *J. sth. Afr. Bot.*, **50:** 159–170.

Cox, J.R., Martin-R., M.H., Ibarra-F., F.A. & Morton, H.L., 1986. Establishment of range grasses on various seedbeds at creosotebush (*Larrea tridentata*) sites in Arizona, U.S.A. and Chihuahua, Mexico. *J. Range Mgmt.*, **39:** 540–546.

Cox, J.R., Martin-R., M.H., Ibarra-F., F.A., Fourie, J.H., Rethman, N.F.G. & Wilcox, D.C., 1988. The influence of climate and soil on the distribution of four African grasses. *J. Range Mgmt.*, **41:** 127–139.

Cox, J.R., Morton, H.L., Johnsen, T.N., Jr., Jordan, G.L., Martin, S.C. & Fierro, L.C., 1982. Vegetation restoration in the Chihuahuan and Sonoran deserts of North America. *U.S. Dep. Agric., Agric. Research Service, Agric. Reviews and Manuals*, ARM-W-28.

Cox, J.R. & Ruyle, G.B., 1986. Influence of climatic and edaphic factors in the distribution of *Eragrostis lehmanniana* Nees in Arizona. *J. Grassl. Soc. South Afr.*, **3:** 25–29.

Crider, F.J., 1945. Three introduced lovegrasses for soil conservation. *U.S. Dep. Agric. Circular* No. 730.

Day, P.R., 1950. Physical basis of particle size analyses by the hydrometer method. *Soil Sci.*, **74:** 181–186.

Fourie, J.H. & Roberts, B.R., 1976. A comparative study of three veld types of the northern Cape: species evaluation and yield. *Proc. Grassl. Soc. sth. Afr.*, **11:** 79–85.

Frasier, G.W., Cox, J.R. & Woolhiser, D.A., 1985. Emergence and survival response of seven grasses for six wet-dry sequences. *J. Range Mgmt.*, **38:** 372–377.

Hausenbuiller, R.L., 1978. *Soil science*. 2nd edition. Dubuque, IA (USA): Brown Publishing Co.

Hendricks, D.M., 1985. *Arizona soils*. Tucson, AZ (USA): University of Arizona Press.

Humphreys, L.R., 1967. Buffelgrass (*Cenchrus ciliaris*) in Australia. *Trop. Grassl.*, **1:** 123–134.

Jackson, M.L., 1958. *Soil chemical analysis*. Englewood Cliffs, NJ (USA): Prentice-Hall, Inc.

Jordan, G.L., 1981. Range reseeding and brush management. *Arizona Agric. Exp. Sta. Bulletin* No. T81121.

Mac Vicar, C.M., Loxton, R.F., Lambrechts, J.J.N., LeRoux, J., Von M. Harmse, H.J.von M., De Villiers, J.M., Vester, E., Merryweather, F.R. & Van Rooyen, T.H., 1977. *Soil classification: A binomial system for South Africa*. Dep. Agric. Tech. Services, Pretoria: Govt. Printer.

Olsen, S.R. & Sommers, L.E., 1982. *Phosphorus*. In: Methods of Soil Analysis, Part II., ed. Page, A.L., Agronomy 9. Madison, WI (USA): Am. Soc. Agron.

Ruyle, G.B., Roundy, B.A. & Cox, J.R., 1988. Effects of burning on germinability of Lehmann lovegrass. *J. Range Mgmt.*, 41: 404–406.

Sanders, J.E., Anderson, A.H., Jr. & Carola, R., 1976. *Physical geology*. New York: Harper and Row Publishers.

Sellers, W.D. & Hill, R.H., 1974. *Arizona climate (1931–1972)*. Tucson, AZ (USA): University of Arizona Press.

Soil Map of the World – Africa., 1977. *Food and agriculture organization (FAO) of the United Nations – United Nations Educational, Scientific and Cultural Organization*. Rome, Italy: Tipolitografia F. Failli.

U.S. Salinity Laboratory Staff., 1954. *Diagnosis and improvement of saline and alkaline soils*. U.S. Dep. Agric., Agric. Handbook No. 60. Washington, DC: Govt. Printer.

Van der Merwe, C.R., 1962. *Soil groups and subgroups of South Africa*. Pretoria: Govt. Printer.

Weather Observational Network: Station Register., 1985. *South African weather bureau*. Pretoria: Govt. Printer.

Wernstedt, F.L., 1972. *World climatic data*. Lemont, PA (USA): Climatic Data Press.