

# The relationship between rainfall, water source and growth for an endangered tree

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**Abstract** It is now reasonably well understood that the human impact on the environment since industrialization has led to significant changes in climate. Here we attempt to develop a predictive understanding of the effects that future changes in climate may have on vegetation structure and species diversity. We do this through a determination of the relationship between radial growth and water source for *Widdringtonia cedarbergensis* Marsh. Our results show that there was no significant relationship between monthly radial growth, as determined using dendrometer bands, and rainfall. There is, however, a significant relationship between the  $\delta^{18}\text{O}$  composition of the water extracted from the trees and the rain  $\delta^{18}\text{O}$  values. We speculate that *W. cedarbergensis* exploits water derived from rain that flows off the rocky substrate of the study area into sumps between the bedding planes of the rocks on which they grow. This runoff occurs rapidly during rain events resulting in  $\delta^{18}\text{O}$  values for the trees sourcing this water not to be significantly different from that of the rain. Rainfall therefore has to be sufficient to refill these sumps on which the trees are dependent. The dendrometer bands reflect a slow but steady growth of the trees at the study site. While this growth is not dependent on rainfall, it is dependent on reliable access to available water. If climate change predictions for the region are realized and rainfall is reduced then this species will be affected. *W. cedarbergensis* is endemic to only a very small area within the Cedarberg Mountains in South Africa and is also one of the few trees growing in the fynbos. The extinction of this species in the wild will fundamentally affect both the vegetation structure and species composition of the region.

**Key words:** climate, dendrometer band, radial growth, rainfall, stable isotope, *Widdringtonia cedarbergensis*.

## INTRODUCTION

It is now reasonably well understood that the human impact on the environment since industrialization (c. 1875) has led to significant changes in climate (Hughes 2000; Walther *et al.* 2002; Thomas *et al.* 2004). The challenge for conservation biologists is in developing a predictive understanding of the effects this climate change may have on vegetation structure and species diversity. While a number of studies have shown that the distribution and abundance of specific species has shifted as a direct consequence of climate change few have directly linked changes in climate to extinction (Thomas *et al.* 2004). There are, however, a number of predictions for both habitat loss and species extinction in the future because of climate change (Hughes 2000; Midgley *et al.* 2002; Thomas *et al.* 2004). Here we attempt to develop a predictive under-

standing of the effects that future climates may have on vegetation structure and species diversity. We do this through a determination of the relationship between radial growth, water source and rainfall for *Widdringtonia cedarbergensis* Marsh.

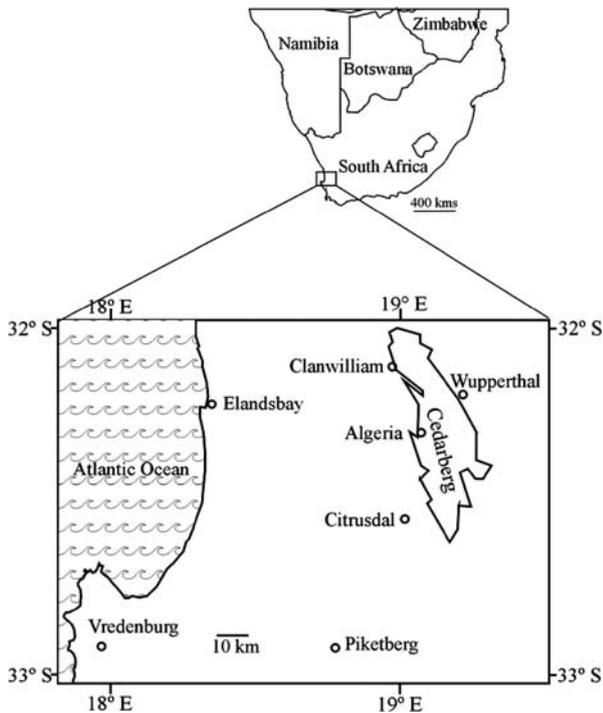
The unique vegetation of the south-western Cape region of South Africa is termed fynbos (Moll & Bossi 1984; Moll & Jarman 1984; Cowling *et al.* 1995; Taylor 1996). The fynbos biome boasts an exceptionally rich diversity of flora (8600 plant species) with high levels of endemism (5800 plant species, Cowling *et al.* 1995). Recent predictions for the region suggest a loss of fynbos area of between 51% and 65% because of climate change (Midgley *et al.* 2002). These predictions suggest that some species will become extinct either as a direct result of physiological stress or via interactions with other species (Midgley *et al.* 2002; Thomas *et al.* 2004).

Midgley *et al.* (2002) suggest that the first indications for climate change effects on plants for the south-western Cape would be in the Cedarberg Mountains approximately 200 km north of Cape Town (Fig. 1). *Widdringtonia cedarbergensis*, also known as the Clanwilliam cedar, is one of the few trees growing in the

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**Fig. 1.** Map showing the location of the Cedarberg Mountains in South Africa.

fynbos and is endemic to the Cedarberg. It has a patchy distribution over approximately 250 km<sup>2</sup> and is confined to the more rocky areas between 900 m and 1400 m above sea level. *Widdringtonia cedarbergensis* is listed as an endangered species, threatened with extinction, if the causal factors for its decline continue to operate (Richardson 1993; Hilton-Taylor 1996). Future predictions for the region are for drier and warmer conditions (Tyson *et al.* 2002; Midgley *et al.* 2003). If this rare and endangered species is reliant on regular rainfall for survival and climate predictions for the region are realized then *W. cedarbergensis* may be pushed into extinction in the wild.

## METHODS

### Study area

The study site is situated at 32°24'51.5"S–19°10'77"E approximately 200 km north of Cape Town, South Africa, at Welbedacht, in the Cedarberg Mountains (Fig. 1). The climate is typically Mediterranean with hot dry summers and cool wet winters. Rainfall, consisting predominantly of frontal systems from the South Atlantic to the west, falls primarily from June to August. The 10-year mean (1994–2004) average annual rainfall at Algeria, approximately 5 km from the study site, is 751 mm (Fig. 1). Average annual

rainfall at the study site, from 2000 to 2004 was 460 mm. Mean monthly maximum and minimum temperatures were 20.0°C and 9.4°C, respectively.

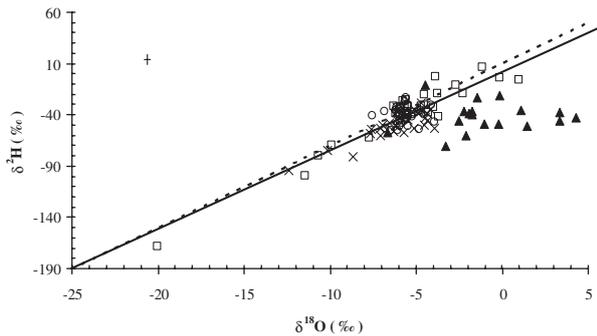
Six *W. cedarbergensis* (Cupressaceae) trees were randomly selected for the study in a variety of positions in the landscape from the top of a rocky outcrop in the north-west corner of the study site, at an altitude of 1375 m a.s.l., to the middle of a small seasonal stream 100 m away, at an altitude of 1272 m, in the south-eastern corner of the site. These trees range in diameter from 26 to 79 cm (mean = 49 cm). The study site is dominated by layers of quartz arenite (sandstones) of the Table Mountain Group (Tankard *et al.* 1982). The trees grow in horizontal fissures between the different strata in the rocks as the soils of the area are extremely shallow (2–3 cm). At this altitude, the other major species coexisting with the *W. cedarbergensis* is *Ischyrolepis sieberi* (Kunth) Linder (Restionaceae). *Ischyrolepis sieberi* grows on the very shallow soils on the rocks forming mats with interlocking rhizomes that can penetrate shallow cracks.

### Diameter growth measures

In October 1999 dendrometer bands (Agricultural Electronics Corporation, Tucson, AZ, USA) were fitted to all six of our study trees. Dendrometer bands are 3 mm × 0.75 mm metal bands placed around the tree and held in place by a spring loaded vernier gauge (Palmer & Ogden 1983; Naidu & DeLucia 1999). Changes in trunk diameter are translated through the metal band to the vernier. This allows changes in tree circumference to be read to the nearest 0.1 mm. The bands were fitted on the trunk below the point at which branching commenced rather than at breast height. To determine the relationship between rainfall and diameter growth of the trees manual readings of the vernier were made at the end of each month from November 1999 to April 2003. We also installed a weather station that measured temperature and rainfall at the site.

### Water source measures

Previous ecological work has shown that the hydrogen and oxygen isotope ratio of water extracted from plants may be used to determine the water source of the plant (White *et al.* 1985; Dawson & Ehleringer 1991). The basis of this method is that within the non-photosynthetic tissue of plants the stable isotope ratio of the water is not changed from its source (White *et al.* 1985; Thorburn & Walker 1993). Therefore, an analysis of the xylem water extracted from the trees or woody rhizome of *I. sieberi* should reflect the stable isotope ratio of the source water used by these different species. Plotting the isotopic composition of this water



**Fig. 2.** The relationship between  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  for all of the water samples from the study showing both our local ( $y = 7.7x + 1.9$ , solid line) and the global ( $y = 8x + 10$ , dashed line) meteoric water lines. Symbols are: (○) Stream water ( $n = 56$ ), (□) Rain ( $n = 20$ ), (▲) *Ischyrolepis sieberi* ( $n = 20$ ), (×) *Widdringtonia cedarbergensis* ( $n = 28$ ). †Reflects two times the range in analytical precision.

in  $\delta$ -space (see Fig. 2) can yield important hydrological and ecological insights. Atmospheric precipitation follows a Rayleigh distillation process resulting in a linear relationship between  $\delta^2\text{H}$  and  $\delta^{18}\text{O}$  of meteoric water samples (Craig 1961). This relationship is called the Global Meteoric Water Line and can be described by the equation  $\delta^2\text{H} = 8 \delta^{18}\text{O} + 10$  (Craig 1961). Free evaporative processes typically describe a line in  $\delta$ -space with a slope of less than 8 (Gat 1996). This results in evaporatively enriched waters, such as surface waters or shallow soil moisture, plotting below the Global Meteoric Water Line in  $\delta$ -space. For plant water-source studies, in arid environments or with shallow soils such as at our study site, these relationships are extremely useful as deep (non-evaporatively enriched) and shallow moisture sources (evaporatively enriched) can be readily distinguished. We constructed a local meteoric water line for the Cedarberg using the stream and rain water samples (Fig. 2).

From October 1999 to March 2002 we collected twig (*c.* 50 mm × 10 mm) samples from each of the six *W. cedarbergensis* trees for stable isotope analysis. At the same time stream water was collected from two locations approximately 100 m apart that bracket the site. Rain was collected in a specially constructed collector comprised of a 500 mL container with a funnel. A layer of paraffin was put into the container to prevent evaporation of the rain, and therefore enrichment of the water. Unfortunately because of the extreme rocky nature of the study site we were unable to obtain soil samples at any depth. For the same reasons we were not able to obtain samples of deeper groundwater which is often isotopically distinct from soil water because of variable recharge inputs (Dawson 1996). Without groundwater or soil samples we used water extracted from the shallow rooted *I. sieberi* each month as a proxy for water from the top 10 cm of the site. We

collected one rhizome sample of *I. sieberi* from August 2000 to March 2002. These twig and rhizome samples were collected into borosilicate tubes (Kimax–Kimble, New Jersey, USA) which could be inserted directly onto a cryogenic vacuum extraction line to separate the water for stable isotope analysis.

After extraction, water samples were analysed for  $^{18}\text{O}/^{16}\text{O}$  ratios using the  $\text{CO}_2$  equilibrium method of Socki *et al.* (1992) while  $^2\text{H}/\text{H}$  ratios were obtained through the closed tube zinc reduction method of Coleman *et al.* (1982). Isotopic ratios of both  $^2\text{H}/\text{H}$  in  $\text{H}_2$  and  $^{18}\text{O}/^{16}\text{O}$  in  $\text{CO}_2$  were determined using a Finnigan Mat 252 Mass Spectrometer (Finnigan, Bremen, Germany) at the University of Cape Town. Our own internal standards were run to calibrate our results relative to Standard Mean Ocean Water (V-SMOW) as well as to correct for drift in our reference gas. The deviation from V-SMOW is denoted by the term  $\delta$  and the results expressed as parts per thousand (‰), through the equation:

$$\delta = (R_{\text{sample}}/R_{\text{standard}}) - 1 \times 1000$$

Where  $R$  = the  $^{18}\text{O}/^{16}\text{O}$  or  $^2\text{H}/\text{H}$  ratio. The analytical uncertainty is approx. 2‰ for  $\delta^2\text{H}$  and approx. 0.2‰ for  $\delta^{18}\text{O}$ .

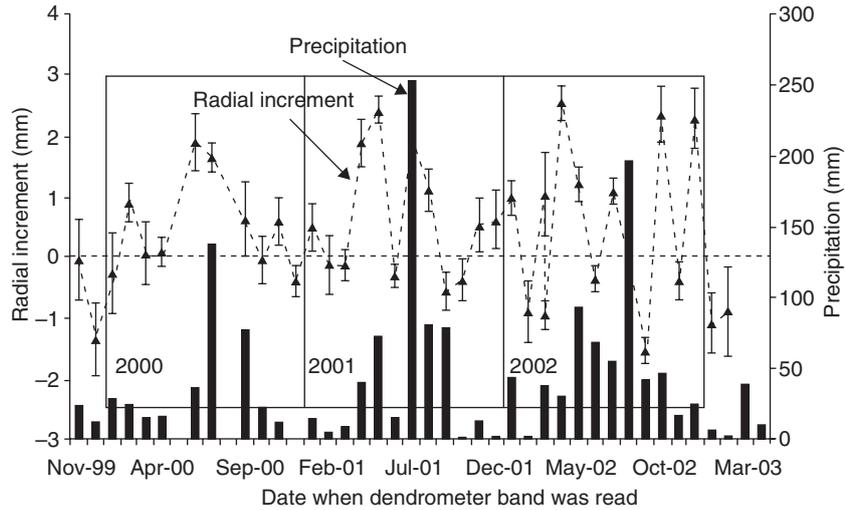
## RESULTS

### Diameter growth measures

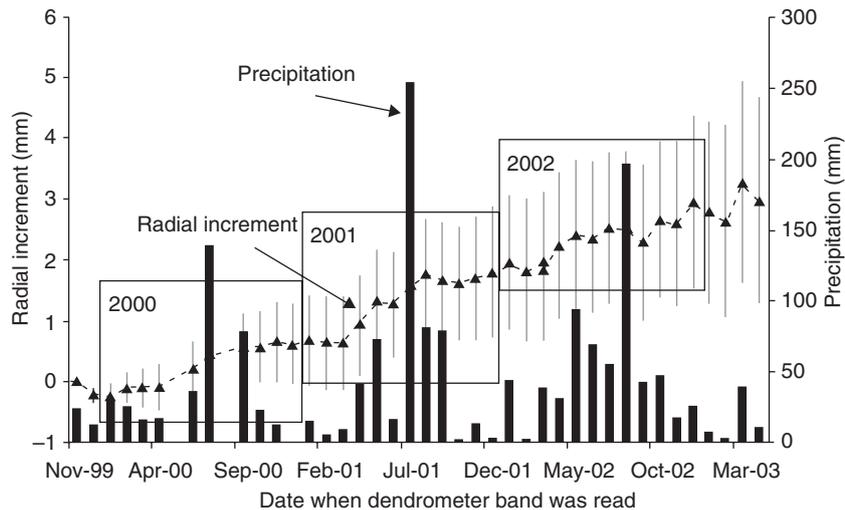
There was no significant relationship between mean monthly increment for the six trees and rainfall from November 1999 to April 2003 (Fig. 3). Inherent within these monthly fluctuations was an incremental increase in radial diameter throughout the study period corresponding with annual growth increments resulting from cambial activity (Fig. 4). Average radial growth for the 3 years of the study was  $3.2 \pm 1.2$  mm. These growth increments are extremely small ranging from an average of  $0.9 \pm 0.5$  mm in 2000 through  $1.1 \pm 0.3$  mm in 2001 to  $1.0 \pm 0.3$  mm in 2002 (Fig. 4). Much of this increase in radial diameter can be attributed to one tree (#4) that had a radial increase of 9.3 mm for the three years of the study which was three times that of the mean for all of the trees.

### Water source measures

There was a significant relationship between the  $\delta^{18}\text{O}$  composition of the water extracted from the trees, and the rain  $\delta^{18}\text{O}$  values ( $n = 28$ ,  $R^2 = 0.67$ ,  $P < 0.0001$ , Fig. 2). There were, however, no significant correlations between  $\delta^{18}\text{O}$  values for the water extracted from *I. sieberi* and the rain  $\delta^{18}\text{O}$  values ( $n = 20$ , NS). The water



**Fig. 3.** Mean monthly radial increments for the six *Widdringtonia cedarbergensis* trees in the study as determined from dendrometer band readings. Histograms are total monthly rainfall. Bars are standard error.



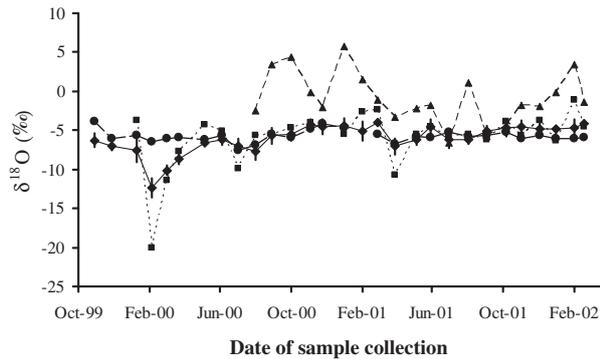
**Fig. 4.** Mean cumulative radial increments for the six *Widdringtonia cedarbergensis* trees in the study as determined from monthly dendrometer band readings. Histograms are total monthly rainfall. Bars are standard error.

extracted from the more deep rooted *W. cedarbergensis* was more negative ( $-6.1\text{‰}$ ) than that extracted from the shallow rooted *I. sieberi* ( $-0.08\text{‰}$ , Figs 2,5). This difference in  $\delta^{18}\text{O}$  results for *W. cedarbergensis* and *I. sieberi* was significant ( $t$ -test:  $P < 0.0001$ ).

Over the study period the  $\delta^{18}\text{O}$  values for the rain varied considerably from  $-20.0\text{‰}$  in February 2000 to  $-1.1\text{‰}$  in February 2002 (Fig. 5). These variations in  $\delta^{18}\text{O}$  values can largely be attributed to the type of rainfall event (Dansgaard 1964; Gat 1996). Thunderstorms and rainfall from the east, moving across the entire continent, resulted in more negative values than the rain out of the Atlantic, 90 km to the west. A close examination of synoptic charts, obtained from the South African Weather Service, for the period showed

that the extremely negative  $\delta^{18}\text{O}$  value of  $-20\text{‰}$  for February 2000 can be related to the cyclone, Eline, that first moved down through the Mozambique channel before swinging inland, with a small tail coming all the way south to the Cedarberg some 2000 km away (the continental effect, Dansgaard 1964; Gat 1996; SA Weather Service 2001).

Mean  $\delta^{18}\text{O}$  values for the ephemeral stream ( $-5.6 \pm 0.7\text{‰}$ ,  $n = 56$ ) that flows through the site are very similar to that of the rain ( $-6.0 \pm 3.7\text{‰}$ ,  $n = 26$ ) and the trees ( $-6.0 \pm 1.9\text{‰}$ ,  $n = 29$ ) but very different to that of *I. sieberi* ( $-0.8 \pm 3.2\text{‰}$ ,  $n = 20$ ). We sampled the stream at the top and bottom of the study site (100 m apart) to control for potential evaporative enrichment. Mean  $\delta^{18}\text{O}$  values at the top of the stream



**Fig. 5.**  $\delta^{18}\text{O}$  values for the study period illustrating the significant correlation ( $n = 28$ ,  $R^2 = 0.67$ ,  $P < 0.0001$ ) between *Widdringtonia cedarbergensis* xylem water  $\delta^{18}\text{O}$  values ( $\blacklozenge$ ) and rain  $\delta^{18}\text{O}$  values ( $\blacksquare$ ). Also presented are the  $\delta^{18}\text{O}$  values for the stream ( $\bullet$ ) as well as the highly enriched  $\delta^{18}\text{O}$  values for *Ischyrolepis sieberi* ( $\blacktriangle$ ).

( $-5.8 \pm 0.7\text{‰}$ ,  $n = 29$ ) was  $0.3\text{‰}$  different from those at the bottom ( $-5.5 \pm 0.8\text{‰}$ ,  $n = 27$ ) of the stream. This difference due to evaporative fractionation was significant ( $t$ -test:  $P < 0.003$ ).

## DISCUSSION

The isotopic ratio of water available to plants reflects the isotopic composition of the precipitation affected by various evaporative processes. Water near the surface of the soil is isotopically enriched due to evaporation of the lighter isotope. With evaporation becoming less effective moving down through the profile, soil water becomes more depleted (Thorburn & Walker 1993; Dawson 1996). Our results follow this trend showing that the trees exploit a deeper water source than the Restionaceae (Figs 2,5). The isotope analysis for *I. sieberi* water samples reflects the isotopic enrichment of the rain on the soil surface due to evaporation indicating that this species uses water very close to the surface (Figs 2,5, Gat 1996). The  $\delta^{18}\text{O}$  values for *W. cedarbergensis*, however, are similar to that of the rain. We suggest that *W. cedarbergensis* exploits water derived from rain that flows off the rocky substrate into sumps between the bedding planes of the rocks in which they grow (cf. Abrams & Orwig 1995). Runoff into these sumps occurs rapidly during rain events when conditions are cool resulting in  $\delta^{18}\text{O}$  values for the trees not significantly different from that of the rain.

The little stream at the bottom of the site is seasonally active, only flowing in the wetter months, as the catchment feeding it is very small and rainfall is often not sufficient to maintain flow. As with many of the streams in the region this stream responds with increased flow within minutes of a rain event (Midgley

*et al.* 2001). The very rocky nature of the study site precludes water infiltration to any depth. Therefore, it is presumably the water between the bedding planes in the rocks that forms the groundwater reserve. We speculate that rain rapidly reaches this reserve and displaces some of the water which then flows out to form the stream. A number of studies have shown that in the Western Cape region of South Africa groundwater has an isotopic signature different from that of the rain (Diamond & Harris 1997; Harris *et al.* 1999; Midgley *et al.* 2001). Without a large groundwater reserve, our monthly rainfall and stream water collection reflected a mean  $\delta^{18}\text{O}$  value for the stream water not very different from that of the rain. The stream water value does not, however, directly reflect the rain isotopic signature as it is buffered to some extent by the ground water reserve (Fig. 5). The isotopic signature of the groundwater should be a weighted average of the inputs over time and space. The close relationship between the isotopic signature of the rain and the stream suggests a small groundwater reserve.

The dendrometer band results do not show that *W. cedarbergensis* is dependent on rainfall at any specific time of the year for growth (Fig. 3). Rather, these results reflect a slow but steady growth of the trees at the study site (Fig. 4). While this growth is not dependent on rain in a particular season it is dependent on reliable access to available water. Rainfall therefore has to be sufficient to refill the sumps between the bedding planes which the trees rely on for available water.

Future predictions for the south-western Cape region of South Africa on the effects of human-induced climate change are for drier and warmer conditions (Midgley *et al.* 2002, 2003; Tyson *et al.* 2002). Midgley *et al.* (2002) have speculated that these changes in climate will lead to a contraction of the fynbos bioclimatic envelope resulting in species extinction. They also suggest that the first indications for these climatically induced extinctions will be in the Cedarberg. Considering the reliance of *W. cedarbergensis* on regular rainfall for available water, if these predictions for the Cedarberg are realized, then this rare and endangered tree will certainly be pushed into extinction. *Widdringtonia cedarbergensis* is one of the few trees growing in the fynbos. Its demise in the wild will fundamentally affect both the vegetation structure and species composition of the region.

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## REFERENCES

- Abrams M. D. & Orwig D. A. (1995) Structure, radial growth dynamics and recent climatic variations of a 320-year-old *Pinus rigida* rock outcrop community. *Oecologia* **101**, 353–60.
- Coleman M. L., Shepherd T. J., Durham J. J., Rouse J. E. & Moore G. R. (1982) Reduction of water with zinc for hydrogen isotope analysis. *Anal. Chem.* **54**, 993–5.
- Cowling R., Richardson D. & Paterson-Jones C. (1995) *Fynbos, South Africa's Unique Floral Kingdom*. Fernwood Press, Cape Town.
- Craig H. (1961) Isotopic variations in meteoric waters. *Science* **133**, 1702–3.
- Dansgaard W. (1964) Stable isotopes in precipitation. *Tellus* **16**, 436–68.
- Dawson T. E. (1996) Determining water use by trees and forests from isotopic, energy balance and transpiration analyses: the roles of tree size and hydraulic lift. *Tree Physiol.* **16**, 263–72.
- Dawson T. E. & Ehleringer J. R. (1991) Streamside trees that do not use stream water. *Nature* **350**, 335–7.
- Diamond R. E. & Harris C. (1997) Oxygen and hydrogen isotope composition of Western Cape meteoric water. *S. Afr. J. Sci.* **93**, 371–4.
- Gat J. R. (1996) Oxygen and hydrogen isotopes in the hydrologic cycle. *Annu. Rev. Earth Planet. Sci.* **24**, 225–62.
- Harris C., Oom B. M. & Diamond R. E. (1999) A preliminary investigation of the oxygen and hydrogen isotope hydrology of the greater Cape Town area and an assessment of the potential for using stable isotopes as tracers. *Water SA* **25**, 15–24.
- Hilton-Taylor C. (1996) Red data list of southern African plants. *Strelitzia* **4**, 1–117.
- Hughes L. (2000) Biological consequences of global warming: is the signal already apparent? *Trends Ecol. Evol.* **15**, 56–61.
- Midgley J. J., Scott D. F. & Harris C. (2001) How do we know how much groundwater is stored in southwestern Cape mountains? *S. Afr. J. Sci.* **97**, 285–6.
- Midgley G. F., Hannah L., Millar D., Rutherford M. C. & Powrie L. W. (2002) Assessing the vulnerability of species richness to anthropogenic climate change in a biodiversity hotspot. *Global Ecol. Biogeogr.* **11**, 445–51.
- Midgley G. F., Hannah L., Millar D., Thuiller W. & Booth A. (2003) Developing regional and species-level assessments of climate change impacts on biodiversity in the Cape Floristic Region. *Biol. Conserv.* **112**, 87–97.
- Moll E. J. & Bossi L. (1984) Assessment of the extent of the natural vegetation of the Fynbos Biome of South Africa. *S. Afr. J. Sci.* **80**, 355–8.
- Moll E. J. & Jarman M. L. (1984) Clarification of the term fynbos. *S. Afr. J. Sci.* **80**, 351–2.
- Naidu S. L. & DeLucia E. H. (1999) First year growth response of trees in an intact forest exposed to elevated CO<sub>2</sub>. *Global Change Biol.* **5**, 609–13.
- Palmer J. & Ogden J. (1983) A dendrometer band study of the seasonal pattern of radial increment in kauri (*Agathis Australis*). *NZ. J. Bot.* **21**, 121–5.
- Richardson D. M. (1993) A review of the work on the Clanwilliam cedar by the South African Forestry Research Institute. In: *Proceedings of the Workshop: The Clanwilliam Cedar: What Is Being Done?* (ed. P. Mustart) pp. 3–5. FCC report. Botanical Society of South Africa, Cape Town.
- SA Weather Service (2000) *Daily Weather Bulletin February 2000*. Republic of South Africa, Government Printers, Pretoria.
- Socki R. A., Karlsson H. R. & Gibson E. K. (1992) Extraction technique for the determination of O-18 in water using pre-evacuated glass vials. *Anal. Chem.* **64**, 829–31.
- Tankard A. J., Jackson M. P. A., Eriksson K. A., Hobday D. K., Hunter D. R. & Minter W. E. L. (1982) *Crustal Evolution of Southern Africa*. Springer Verlag, New York.
- Taylor H. C. (1996) Cederberg vegetation and flora. *Strelitzia* **3**, 1–75.
- Thomas C. D., Cameron A., Green R. E. *et al.* (2004) Extinction risk from climate change. *Nature* **427**, 145–8.
- Thorburn P. J. & Walker G. R. (1993) The source of water transpired by *Eucalyptus camaldulensis*: soil, groundwater, or streams? In *Stable Isotopes and Plant Carbon-Water Relations* (eds J. R. Ehleringer, A. E. Hall & G. D. Farquhar) pp. 511–27. Academic Press, San Diego.
- Tyson P., Odada E., Schultze R. & Vogel C. (2002) Regional-global change linkages: Southern Africa. In: *Global-Regional Linkages in the Earth System* (eds P. Tyson, R. Fuchs, C. Fu *et al.*) pp. 3–73. Springer, Berlin.
- Walther G. R., Post E., Convey P. *et al.* (2002) Ecological responses to recent climate change. *Nature* **416**, 389–95.
- White J. W. C., Cook E. R., Lawrence J. R. & Broecker W. S. (1985) The D/H ratios of sap in trees: implications for water sources and tree ring D/H ratios. *Geochimica Cosmochimica Acta* **49**, 237–46.