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Review

Provision of watering points in the Australian arid zone: a review of effects on biota

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In this paper we review the effects of the provision of artificial sources of water on native flora and fauna in arid and semi-arid zones, with emphasis on Australia but drawing on information from other countries where possible. The effects of artificial sources of water are profound and are a rarely-cited aspect of change in arid and semi-arid zone rangelands. Direct effects of artificial sources of water include: (1) the development of wetlands that support native plants and animals; (2) the expansion of geographic range and increased abundance of native animals which need to drink regularly; and (3) the possible expansion of breeding ranges of invertebrates that require water for some stage of their life cycle. The major indirect effects of artificial sources of water are as a source of drinking water for domestic stock, and native and feral mammalian herbivores, and so they provide a focus for grazing. Recorded changes in vegetation in response to grazing around artificial sources of water are: (1) the development of a zone of extreme degradation around the water (up to 0·5 km) where soil crust is broken, erosion is high and unpalatable plants dominate; (2) an increase in the number of unpalatable perennial shrubs beyond the extreme degradation zone, particularly in semi-arid woodland and arid shrubland habitats; and (3) a decrease in abundance of palatable native perennial grasses due to selective grazing. Effects of grazing on native fauna are poorly documented but published accounts include: (1) a possible contribution to the recent extinction of some medium-sized native mammals in Australia, also assisted by those introduced predators which rely on drinking water; (2) the displacement of some ground-dwelling bird species from regions heavily developed for pastoralism, and geographic range reductions for many other species of birds; and (3) changes to the distribution and abundance of invertebrates such as grasshoppers, ants and collembolans. Artificial sources of water may also indirectly affect native wildlife by acting as foci for the activities of native and introduced predators.

Keywords: bore; dam; grazing; water; piosphere; rangeland; arid zone; biodiversity

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Introduction

The effect of European settlement on the biota of Australia has been profound. Attention tends to be focused on the agricultural zones, possibly because clearing, fragmentation, erosion and salinity are visibly obvious problems (e.g. Saunders & Hobbs, 1991; Saunders *et al.*, 1991, 1996). Although the changes that have occurred in the arid and semi-arid zones of Australia are less visibly obvious, they are nevertheless substantial. The arid and semi-arid zones constitute over 70% of the continental land area (Fig. 1) and within them one-third (12 species) of the mammal species that formerly occurred there are now extinct (Burbidge & McKenzie, 1989; Morton, 1990; Woinarski & Braithwaite, 1990). Grazing and agriculture combined are also the presumed cause of the extinction of 78 species of plants, and a major threat to the survival of a further 105 plant species (State of the Environment Advisory Council, 1996). On a world scale these figures are daunting. They represent 20% of all global

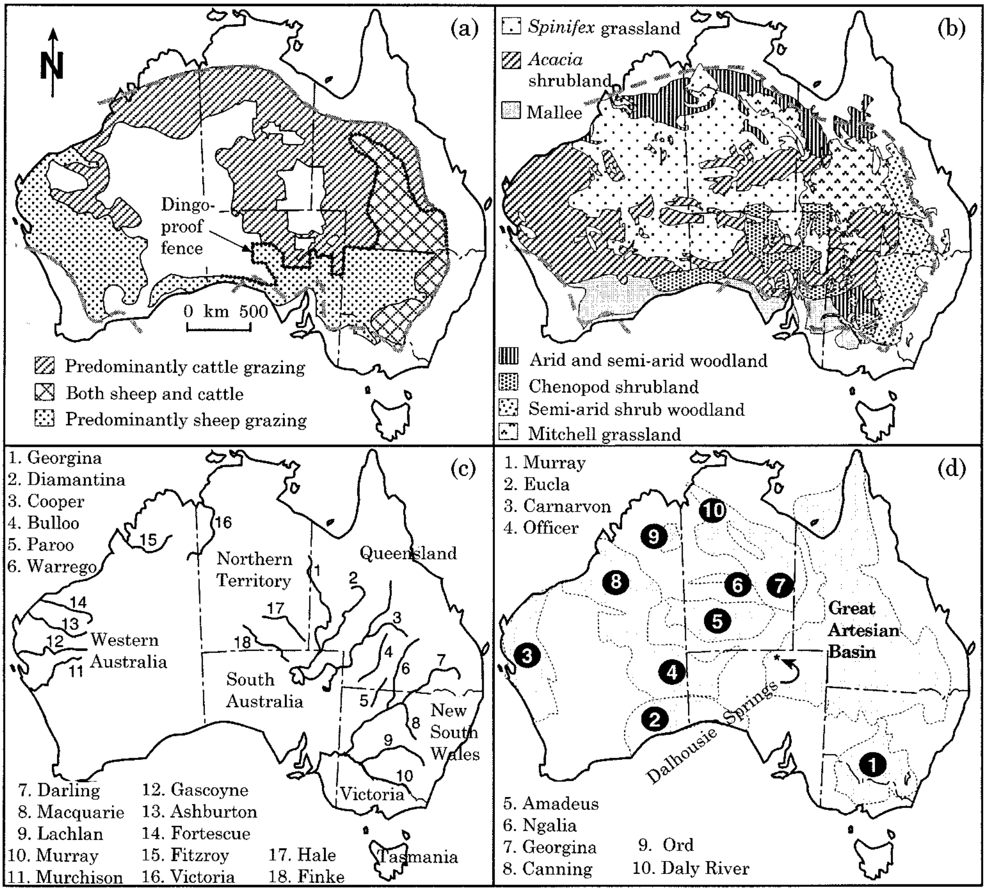

Figure 1. (a) Distribution of rangeland grazing in Australia, within the arid and semi-arid zones, indicated by the thick dashed line (adapted from Plumb, 1982), and the original outline of the dingo-proof fence as a dotted line; (b) major vegetation biomes of the arid and semi-arid zones of Australia (adapted from Moore & Perry, 1970); (c) major river systems and waterways, some of which are referred to in the text (adapted from Reader's Digest Atlas of Australia, 1968); and (d) major underground sources of water in the arid and semi-arid zones of Australia (adapted from Australian Water Resources Council, 1976).

extinctions of mammals and 14% of vascular plants (World Conservation Monitoring Centre, 1992). More than half of Australia's endangered mammal species, more than a third of Australia's threatened bird species, one of 11 threatened reptile species and about 3% of Australia's threatened plant species occur in the arid and semi-arid zones (Woinarski & Braithwaite, 1990; Hoser, 1991; Leigh & Briggs, 1992; Reid & Fleming, 1992). This record of species loss, and the potential for many more extinctions, has led to a focus on the effects of current land uses on biodiversity.

Throughout most of the arid and semi-arid zones of Australia, the primary land use is rangeland pastoralism where domestic stock have been introduced to graze native vegetation. These areas have been altered from their natural state by direct actions to support a pastoral industry. Among these alterations are the provision of artificial sources of water; the introduction of cattle and sheep as grazing animals over much of the area; the introduction of exotic species as forage (e.g. buffel grass, *Cenchrus ciliaris*; Humphries *et al*., 1992) in some areas; the elimination of a major predator, the dingo (*Canis familiaris dingo*), from most areas where sheep are grazed; and clearing of overstorey trees in some areas. But many changes have also occurred in the arid and semi-arid zones either indirectly linked to or unrelated to pastoralism. These include: an increase in the abundance of some species of kangaroos (Newsome, 1965, 1975; Caughley *et al*. 1980); the introduction of many non-native animals (rabbits, goats, horses, camels, donkeys, pigs, cats and foxes) that have since become widespread and often abundant (Wilson *et al*., 1992); a decline in the abundance of many species of plants, including palatable perennial species (Leigh & Briggs, 1992); an increase in abundance and distribution of many species of unpalatable perennial shrubs (Harrington *et al*., 1984; Wilson, 1990; Ralph, 1991); the extinction of many species of native mammals and the decline in abundance and geographic range of many of the remaining species (Morton, 1990); and altered fire regimes (Hodgkinson & Harrington, 1985).

For many organisms, water is the key to biological activity in arid and semi-arid zones. A lack of water causes inactivity or death more rapidly than a lack of any other essential resource such as food and nutrients. In an unmodified condition, the Australian arid and semi-arid zones have few permanent natural waters (James *et al*., 1995). In most countries, including Australia, artificial sources of water in arid areas are now so common and reliable that the term drought has taken on a functionally different meaning. Water is available *ad libitum* to most mobile animals. With the provision of artificial sources of water, herbivorous mammals are able to continue to graze country that has had no rainfall, whereas before they would have died or abandoned such country because of the lack of drinking water. The result is removal of vegetation, chiefly perennial grasses and palatable shrubs, before populations of mammalian herbivores begin to decline. In most regions today, lack of rainfall usually results in feed shortages but not shortages of drinking water.

Research into rangeland management has focused primarily on productivity, stocking rates and efficient use of forage (e.g. Harrington *et al*., 1984). Until recently there has been little emphasis in Australia and North America on the effects of water points on the distribution and abundance of native species that inhabited these previously dry regions. In Africa, however, the provision of permanent artificial sources of water for domestic stock, to sustain wildlife which has been prevented from continuing seasonal migrations due to human barriers (Kalikawa, 1990) and to maintain populations of game within national park boundaries (Ayeni, 1975), has led to concerns about their effects in previously dry landscapes (Collinson, 1983; Thrash, 1998).

In this review we examine the direct and indirect effects of the provision of artificial sources of water in previously dry landscapes. The literature on this topic deals mostly with water provided for domestic livestock, although in Africa water is provided for wildlife as noted above. Although the patterns of development of pastoral industries are similar for arid zones around the world, the details of the situation are substantially different on each continent. Therefore, for simplicity and thoroughness we discuss mainly the literature for Australian ecosystems. We draw on literature from other countries where it is possible to make comparisons and generalizations.

A brief history of the development of pastoralism in the arid and semi-arid zones of Australia

Sources of water

Artificial sources of water can be generated from ground-water or from trapping and storing surface runoff in constructed dams. Ground-water is tapped by drilling a bore hole whereupon water either flows to the surface because of subterranean pressure (artesian) or must be pumped to the surface (sub-artesian; Roberts, 1978). Once at the surface, water from bores can be allowed to run along natural or artificial depressions ('bore drains') or can be stored in metal, plastic, stone or earth tanks before being reticulated to points where stock drink. We will refer to water that comes from ground-water as borewater regardless of how it is gathered and made available. Artificial sources based on ground-water are usually permanent.

Some pastoral regions of Australia do not have access to ground-water and in these areas water must be trapped in dams. Dams usually hold sufficient water to last for months to years. Water trapped in dams can also be reticulated to provide water at distant locations.

Pastoralism in Australia

Rangeland pastoralism occurs on 53% of the land area of Australia, and 70% of the arid and semi-arid zones. The southern areas are mostly grazed by sheep and the central and northern areas by cattle. This split is partly because of differences in climatic tolerances of stock, and partly because predation on sheep by dingos is too high outside the area bounded by the dingo exclusion fence (Fig. 1(a)). The vegetation biomes within the arid and semi-arid zones are shown in Fig. 1(b); not all of these are useful for grazing by stock. In eastern Australia, the main rangeland biome is the semi-arid shrub woodlands consisting of mulga (*Acacia aneura*) and poplar box (*Eucalyptus populnea*)-dominated lands of western New South Wales and southern Queensland (Harrington *et al*., 1984). Chenopod shrublands, dominated by species of *Atriplex* (saltbushes), *Maireana* (bluebushes), *Chenopodium* and *Sclerolaena* (Graetz & Wilson, 1984), are predominantly found in southern Australia where most rainfall comes in winter (Fig. 1(b)). The mallee biome also spans the southern part of the continent and is structurally and floristically dominated by species of *Eucalyptus* that grow multiple aerial stems from a lignotuberous rootstock (Noble, 1984), and groundcovers of spinifex (*Triodia* spp.), annual grasses (*Stipa* spp.) or chenopodiaceous shrubs. Mitchell or tussock grasslands of *Astrebla* spp. are grazed mainly by cattle and found on alkaline cracking soils in a band across the northern part of the tropical semi-arid belt where summer (wet season) rainfall predominates (Orr & Holmes, 1984; Orr & Evenson, 1991). Spinifex grasslands occupy 22% of Australia's land area and $>30\%$ of the area of the arid and semi-arid zones. They are floristically dominated by endemic grasses of the genera *Triodia* and *Plectrachne* and are virtually unused for pastoralism because of the poor nutritional value of the grass (Griffin, 1984). *Acacia*-dominated woodlands are second in extent only to the spinifex grasslands, covering 25% of the arid and semi-arid zone rangelands. In the west and east the overstorey is dominated by mulga (*Acacia aneura*), but in central Australia the overstorey includes ironwood (*Acacia estrophiolata*) and gidgee (*A. georginae*) as dominants (Foran, 1984;

Morrisey, 1984). The groundlayer vegetation consists of various species of grasses (e.g. *Aristida*, *Eragrostis*, *Monochather*, *Enneapogon*, *Digitaria* and *Enteropogon* spp). Arid and semi-arid low woodlands are communities with dominant overstorey up to 8 m. In the south they are dominated by callitris pine, belah and rosewood, and in the north by *Eucalyptus brevifolia*, *E. argillacea*, *E. terminalis* and lancewood (*Acacia shirleyi*; Moore, 1970).

Grazing leases were established over much of eastern and southern Australia (New South Wales, Queensland and South Australia; Fig. 1(c)) by the mid-19th century, and in central and Western Australia in the mid 1880s. Before the discovery of ground-water or the development of technologies for large-scale earth works, pastoralism was focused on the permanent and semi-permanent waters of the major waterways and their tributaries, shown in Fig. 1(c) (Condon, 1983). During seasons of high rainfall animals could walk away from the rivers to graze but most of the grazing pressure was on the riparian habitats associated with the river frontages. Even with this uneven distribution of grazing pressure, notable changes such as shrub removal and soil erosion had taken place as a result of pastoralism after only a few years of use (Proceedings of the Parliament of South Australia, 1868; Harrington *et al*., 1979).

The Great Artesian Basin (Fig. 1(d)) was discovered when a bore hole was drilled between the Darling and Paroo Rivers in 1878 (Ward, 1950; Habermehl & Seidel, 1978). The discovery of artesian water and the development of machinery to excavate dams led to the creation of a few artificial sources of water by the 1890s (Noble & Tongway, 1983*a*). But watering points were still sparse so much of the country could not be grazed. Compared with management today, large numbers of sheep were watered at each bore or dam (Pickard, 1990). As a result, stocking rates in the accessible area around watering points were much greater than could be sustained. This situation led to the build-up of extraordinarily large stock numbers in eastern and southern Australia by the end of the 19th century. Inevitably, the combined effects of drought and overstocking led to a crash in stock numbers (Ratcliffe, 1936; Friedel *et al*., 1990) and an enormous toll on the integrity of rangeland ecosystems.

Not until the 1950s were large numbers of artificial sources of water established. A series of favourable seasons in eastern Australia, high wool prices and government subsidies gave pastoralists the opportunity to invest in capital improvements such as bores (Noble & Tongway, 1983*a*). The Great Artesian Basin is the most significant artesian water source in Australia because of its size (1·7 million km^2) and the amount of water it provides. By 1970 there were around 3000 artesian bores and more than 20,000 sub-artesian bores yielding 1500 million l per day (Fisher, 1969; Habermehl & Seidel, 1978). In eastern Australia, as the number of artificial sources of water increased, property sizes were reduced, and fencing of paddocks reduced the number of animals drinking at each watering point from the thousands seen in the early part of the century to a few hundred. Smaller flocks placed less stress on the environment around individual watering points. In recent times research into the way in which stock forage (Low, 1974; Low *et al*., 1978; Foran, 1980) has led to recommendations that watering points should be distributed evenly and closely across paddocks to give the most efficient utilization of forage with least damage to the soil (Lange *et al*., 1984). To achieve high density and close spacing of water points, it is now common to use polyethylene pipes to reticulate water from existing bores and dams. Thus, the process of 'watering' the arid and semi-arid zone rangelands of Australia continues.

Density of artificial sources of water in Australia

Artificial sources of water are now found at high densities over very large areas of the arid and semi-arid zones of Australia. Landsberg & Gillieson (1996) mapped all named

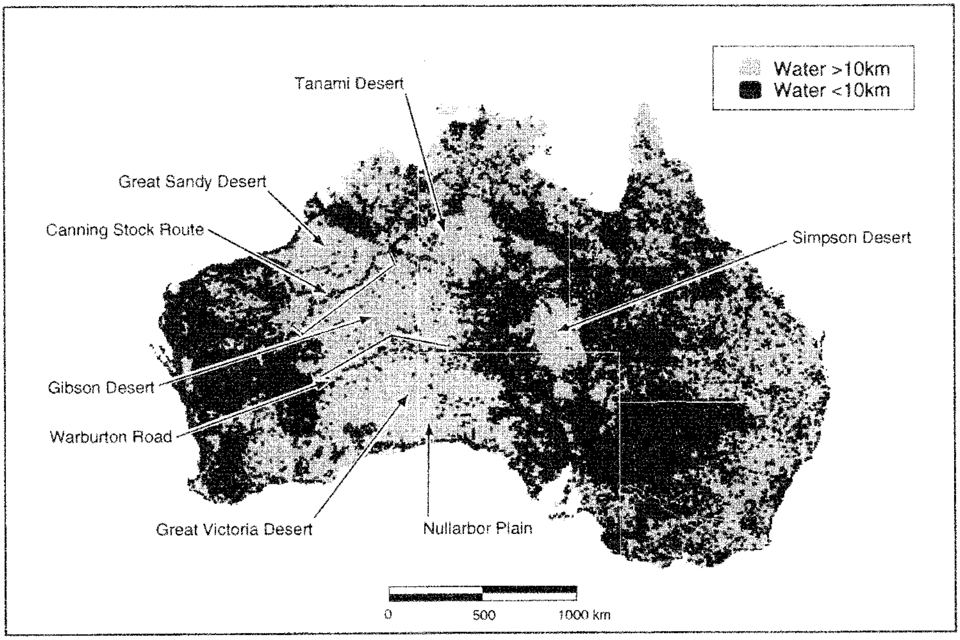

Figure 2. The proliferation of water points in the Australian arid zone is illustrated in this map, which shows only the *named* water points on the 1:250,000 and 1:100,000 series of topographic maps. Each named water point is surrounded by a buffer of 10 km radius. Not all water points on arid zone maps are named, so the density of water points in the arid zone is much higher than shown. Large areas of the major deserts and the Nullarbor Plain are remote from named water points, but much of the rest of the arid zone is well supplied with water. Large areas of eastern Australia are also shown as being remote from named water points, but, unlike the deserts, these regions are well provided with unnamed artificial sources of water (e.g. farm dams, and creeks, rivers and bore drains) (From James *et al.* (1995) with permission.)

watering points from the 1:250,000 topographic map series (AUSLIG, 1986; digital data) for arid and semi-arid zones and found that only the desert regions (Simpson, Tanami, Gibson, Great Sandy and Great Victoria Deserts; Fig. 2) had substantial areas that were more than 10 km from a named watering point. Furthermore, they analysed a sample of map sheets more closely to find that only 29% of watering points were named, suggesting that average distances between watering points were in fact substantially less than 10 km.

Morrisey (1984) reported artificial sources of water at an average density of one per 4000 ha in sheep-dominated, and one per 10,000 ha in cattle-dominated mulga woodland rangelands in Western Australia (a total area of 700,000 km^2; Fig. 1(b)). These figures equate to an average distance between waters of 7 km and 11·2 km for sheep and cattle lands, respectively. Jarman & Denny (1976) report that the average spacing of water points in mulga woodland habitats of northern New South Wales and eastern South Australia was 5·5 km on sheep properties and 11·0 km on cattle properties. Similarly, in the same biome in south-west Queensland (Fig. 1(b)), the number of artificial sources of water varies from around 850 to over 1000 bores and dams per 1:250,000 map sheet, an area of 16,800 km^2 (Ross Blick, pers. comm.). Assuming a uniform spacing between watering points, this represents one watering point per 17 km^2, or an average spacing of around 5 km between watering points. These figures indicate that over large areas there is little land beyond about 2–3 km from water in areas where sheep are grazed, and beyond about 6 km where cattle are grazed. In addition to bores and dams, in south-west Queensland there are 1000 to >2000 km of bore drain shown on each 1:250,000 map sheet (Ross Blick, pers. comm.) resulting in substantially smaller areas distant from water.

General effects of grazing from artificial sources of water

The piosphere

Osborn *et al.* (1932) were the first in Australia to recognize the radial symmetry in grazing intensity that develops around watering points and to examine the effects of grazing on vegetation along transects radiating from a watering point. In North America, Valentine (1947) also drew attention to the declining use of forage away from an artificial source of water in a black gramma (*Bouteloua eriopoda*) grassland in the Chihuahuan Desert. Subsequently, Lange (1969) coined the term piosphere for this radial grazing pattern.

Grazing impact is greatest close to a watering point and decreases with distance from the water for two reasons: (1) the area available to graze increases with distance from the focal point resulting in a reduction in density of stock; and (2) stock have to drink regularly so they are limited in how far they can travel from water. As well as grazing effects, there are also effects from trampling and dust associated with the movement of animals close to the watering point (Andrew & Lange, 1986*a*). Trampling is most obvious within a few hundred metres of the watering point, an area often called the ‘sacrifice zone’ (Valentine, 1947).

In relatively uniform landscapes such as chenopod shrublands radial symmetry of use around artificial sources of water should develop (Lange, 1969; Andrew, 1988). However, piospheres are usually ‘warped’ by the constriction of fencelines (Lange, 1969) or by preferences for particular types of vegetation that cause grazing pressure to be disproportionate to the distance from water (Low *et al.*, 1973; Lynch, 1977; Graetz, 1978; Fatchen & Lange, 1979; Lange, 1985; Pickup & Chewings, 1988; Van Rooyen *et al.*, 1994). Sheep graze and move head-first into the wind, so there is greater grazing pressure on parts of the paddock that are toward the prevailing wind direction from the watering point (Orr, 1980; Andrew & Lange, 1986*a*). In very hot conditions, the lack of available shade may force stock to move further than is necessary simply to graze (Orr, 1980; Bosch & Gauch, 1991). Also, saline water and forage may limit distances moved from water (Stafford Smith, 1988). So while grazing impact around artificial sources of water generally decreases with increasing distance, other factors can cause substantial variation in the pattern. This variation is one reason why it has been difficult to monitor change in range condition caused by grazing (Bastin *et al.*, 1993*a*).

Recently, techniques have been developed to assess vegetation-cover change in central Australia from satellite data, and hence to assess the effect of grazing over large areas relatively inexpensively (Pickup *et al.*, 1994). These techniques involve using reflectance values in red and green wavelengths to generate an index of long-term grazing effects (Bastin *et al.*, 1993*b*; Pickup *et al.*, 1993). Similar techniques have been used to examine piosphere effects around bores in the Sahel region of Africa (Hanan *et al.*, 1991).

Distances travelled from water by water-dependent mammalian herbivores in Australia

The distance from water that stock will travel to feed is a balance between water demands driven by temperature, physiology and body condition, and the availability of forage. For cattle in central Australia, mesic periods when forage is of high quality result in cattle movements of only 4 km from water (Hodder & Low, 1978). Under dry conditions, when feed is sparse or of poor quality, movements up to 10 km result (Hodder & Low, 1978), and in very poor quality habitat, or during winter, cattle may occasionally move over 20 km from water (Low *et al*., 1978).

Sheep grazing is similarly constrained in southern rangelands. That is, high temperatures in summer necessitate frequent drinking, while wet conditions and low temperatures in winter allow sheep to forage away from permanent watering points for long periods, relying on ephemeral water and the moisture content of the forage (Osborn *et al*., 1932; Wilson, 1978). Under hot conditions, the foraging range of sheep is reduced to 3 km (Lange, 1969; Lynch, 1974; Squires, 1976, 1978). Chenopod shrubs are high in minerals and animals eating this vegetation must drink larger quantities of water to flush the salts from their bodies (Wilson & Graetz, 1980).

Most grazing in Australian rangelands is done by domestic stock (cattle and sheep), but in some areas the numbers of other grazing animals can be significant. In parts of the rangelands of northern New South Wales and southern Queensland, kangaroos and goats are at least equal to sheep in abundance and therefore contribute more than half of the total grazing pressure (Landsberg & Stol, 1996). Red kangaroos (*Macropus rufus*), eastern grey kangaroos (*M. giganteus*), western grey kangaroos (*M. fuliginosus*) and euros (or wallaroos, *M. robustus*) can attain high densities in pastoral land, mostly where the dingo has been removed (Newsome, 1975; Caughley *et al*., 1980). Red kangaroos and euros have much lower water requirements than sheep or goats (Dawson *et al*., 1975), and therefore they may travel further and stay away longer from water than stock (Ealey, 1967). Goats (*Capra hircus*) are similar to sheep in their water requirements (Dawson *et al*., 1975) and therefore are probably similar in their ability to travel away from water to graze. Feral horses (*Equus caballus*) need to drink less frequently and can travel further than cattle (Berman & Jarman, 1987). However, they prefer to stay close to water points unless forced to travel longer distances for preferred grasses; this may occur during droughts when forage is eaten out close to water (Dobbie *et al*., 1993). Morphological and physiological adaptations allow camels (*Camelus dromedarius*) to be less dependent on free water than other large mammals (Schmidt-Nielsen *et al*., 1956); they can go for periods of 4 days (summer) to 89 days (winter) without drinking (Dörges & Heucke, 1996) and range furthest from natural or man-made watering points between drinks. The camels' ability to disperse far from water points and their current low density means that in Australia grazing gradients caused by them are probably diffuse and obscure.

Abiotic effects

Soils in arid environments worldwide are generally nitrogen- and phosphorous-deficient, and soils in arid Australia are generally more deficient than those in other countries (Charley & Cowling, 1968; Stafford Smith & Morton, 1990). Most nitrogen available to plants is held in the top 10 cm of soil as a result of breakdown of organic matter (Charley & Cowling, 1968) and nitrogen-fixing algae in cryptogamic crusts (Mayland & MacIntosh, 1966; but see Snyder & Wullstein, 1973 for an alternative view on the role of cryptogamic crusts in providing nitrogen). Heavy traffic by stock breaks up the cryptogamic crust (Eldridge, 1996) which has two consequences: (1) the nitrogen-fixing action of the cryptogams is disrupted; and (2) the soil surface is loosened allowing wind and water erosion to remove surface layers. Charley & Cowling (1968) suggested that removal of this vital surface layer prevented regeneration of degraded chenopod shrublands in southern Australia.

Compaction of the soil surface due to stock traffic is well documented for non-arid regions, but there remains little evidence of widespread compaction in arid and semi-arid zone rangelands (Lee, 1977). Compaction appears to be restricted to heavy stock-traffic areas such as around watering points and along tracks (Lee, 1977; Eldridge, 1996). Compaction of soil along sheep tracks reduces infiltration (Tunstall & Webb, 1981; Noble & Tongway, 1983*b*), thus altering soil water balance (Marshall, 1974), but the direct impact of altered soil water balance on biota does not appear to have been examined. In areas of heavy grazing, it is not only the cumulative weight of many animals that compacts the soil, but the destruction of soil macropores created by burrowing invertebrates and plant roots that reduces infiltration (Elkins *et al*., 1986; Lobry de Bruyn & Conacher, 1990; Whitford *et al*., 1992; Greene *et al*., 1994).

The accumulation of dung and urine from grazing animals is proportionally related to the distance from permanent water in a number of systems, including sheep in Australian chenopod shrublands (Lange, 1969, 1985; Lange & Willcocks, 1978; Andrew & Lange, 1986*a*), kangaroos in semi-arid woodlands (Gibson, 1995), cattle in the Chihuahuan Desert (Fusco *et al*., 1995) and large mammals in Africa (Weir, 1971; Tolsma *et al*., 1987; Thrash *et al*., 1995). A benefit of accumulation of dung and urine from grazing mammals close to the watering point is the nutritive input to soils and grasses leading to greater productivity (Weir, 1971; Georgiadis & McNaughton, 1990; Perkins & Thomas, 1993*a*). However, Noy-Meir & Harpaz (1976) believed that little of the potentially available nitrogen in dung and urine is actually available for use by plants.

Effects of artificial sources of water on biodiversity

We identify four ways in which artificial sources of water can affect native biota: (1) they are a focus for drinking by grazing mammals which results in changes due to grazing and trampling; (2) they are a focus for drinking by non-domestic water-dependent animals; (3) they produce wetland habitats created from dams and free-flowing bores which influence the distribution of water-dependent species; and (4) they are a focus for hunting, scavenging and drinking by predators. These effects are documented and discussed in the following sections.

Effects of grazing by large herbivorous mammals

The main reason for the establishment of large numbers of artificial sources of water in arid zones around the world has been for watering domestic stock and native wildlife. Hence, the most obvious effects of artificial sources of water are those associated with grazing and trampling by large herbivorous mammals. The effects of this grazing and trampling on plants and soils have been widely studied, and much of the pertinent literature has been reviewed recently by West (1993*a*,*b*), Fleischner (1994), James *et al*. (1995) and Landsberg *et al*. (1999). Here we do not attempt to list this literature comprehensively, but give an overview with most emphasis on arid and semi-arid Australia.

Effects of grazing on rangeland plant communities

Two general trends emerge from studies of the effects of different grazing intensities on rangeland plant communities: grazing at moderate densities leads to higher within-habitat species richness compared with grazing at low or high densities (Archer *et al*., 1987; Wilcox *et al*., 1987; Andresen *et al*., 1990; Chaneton & Facelli, 1991); and very heavy grazing results in a decline in the number of species, a reduction in abundance of the remaining species and dominance by a few species (O'Connor, 1991; Pandey & Singh, 1991; Fusco *et al*., 1995). These empirical patterns have supported the use of the intermediate disturbance hypothesis to explain responses of plant communities to grazing (Miller, 1982; Crawley, 1983; Sousa, 1984; Collins & Barber, 1985; Shmida & Wilson, 1985; Facelli, 1988). However, refinement of the intermediate disturbance hypothesis for grazed ecosystems is necessary because a bell-shaped response to a gradient of grazing intensity is not necessarily expected in regions with different evolutionary histories of grazing use or climate (Milchunas *et al*., 1988; Milchunas & Lauenroth, 1993).

Another approach to studying the effects of grazing in rangelands has been to examine changes in species composition, abundance or community structure of vegetation along gradients, varying from a few hundred metres to several kilometres around artificial sources of water. A number of general patterns emerge. (1) The area immediately around a watering point is often degraded because trampling and grazing by animals returning regularly to water inevitably leads to pulverization of the soil surface and accumulation of dung and urine. This area can be bare during dry periods but supports short-lived, often unpalatable, trample-resistant 'increaser' species after rain. (2) There is often a zone of dense unpalatable perennial woody shrubs beyond the denuded area around a watering point. Substantial changes in the species composition and cover of vegetation occur within this zone. (3) Palatable perennial plants decline in abundance and species richness within the two zones mentioned above, and also beyond them. Below, we elaborate on these general patterns for Australian ecosystems, with some examples from other countries.

Chenopod shrublands. Close to watering points (0–400 m) there is lower biomass of the most palatable shrub species with increased density of less palatable species compared to areas at greater distance. Dominant perennial shrub species (*Atriplex* and *Maireana* spp.) are replaced by annual chenopod subshrubs, forbs or annual grasses (Osborn *et al*., 1932; Fatchen, 1978; Graetz, 1978; Graetz & Ludwig, 1978; Barker, 1979; Andrew & Lange, 1986*b*; Wilson, 1990). Although there is a general trend for reduced biomass of palatable perennial species with increasing distance from water, there is considerable variation in the expression of this trend (Osborn *et al*., 1932; Graetz, 1978). Sigmoid equations best describe changes in ground cover in gradients away from watering points up to 2–3 km where shrub cover seems to reach a stable maximum (Graetz & Ludwig, 1978). In the studies noted above, species richness did not change consistently with distance from artificial sources of water.

Semi-arid shrub woodlands and Acacia*-dominated shrublands*. There has been a major shift in the composition of understorey vegetation, particularly of grasses, in the *Acacia*-dominated woodlands and shrublands. Over a range of grazing intensities from heavy to moderate, palatable perennial grasses (e.g. *Thyridolepis mitchelliana* and *Themeda australis*) have been replaced by unpalatable species, mainly *Aristida* spp. (Harrington *et al*., 1979; Hodgkinson, 1991, 1992). Sustained heavy grazing over large areas may lead to the local extinction of some grass species because of depletion of the seed bank in the soil (Hodgkinson, 1992).

Acacia-dominated woodlands and shrublands have also become dominated by unpalatable native shrubs of *Eremophila*, *Senna*, *Dodonaea* and *Acacia* spp. (Harrington *et al*., 1979; Friedel, 1981; Friedel *et al*., 1990). Shrub increase is undoubtedly linked to increased grazing pressure associated with artificial sources of water, although there is still debate about the balance of the mechanisms. Shrubs appropriate resources (water and nutrients), preventing grasses from re-establishing; reduced fuel loads and lower fire frequencies further promote shrub establishment (Moore, 1973; Harrington, 1979; Harrington *et al*., 1979; Hodgkinson & Harrington, 1985; Friedel, 1991).

As a result of these effects, vegetation along transects away from watering points undergoes major changes in species composition and cover: unpalatable species are abundant and ground cover is usually low near watering points, and ground cover increases at greater distances (Foran, 1980; Cowley, 1994; Cowley & Rogers, 1995). These trends are mirrored by species present in the soil seed bank along a similar gradient from water: dominance of heavily grazed sites near water by annual and generally unpalatable species which decline with increasing distance from water (Navie *et al*., 1996). Trends in species richness with increasing distance from a watering point in central Australia showed no change for many sites, however a few locations did have higher species richness at water-remote sites (Friedel, 1997).

Mitchell grasslands. Sites close to water points tend to be dominated by annual grasses, especially during the wet season when they grow most strongly. Perennial grass cover (*Astrebla* spp.) increases with increasing distance from water (Fisher, 1996), and under moderate to light grazing intensity *Astrebla* grasslands appear to be quite resilient (Orr, 1980; Orr & Evenson, 1991). Thus, this system parallels others with annual species tending to be increasers and perennials tending to be decreasers under moderate to heavy grazing pressure. Lightly grazed sites, or exclosed areas that have not been grazed, had a greater number of perennial grass species (Orr, 1980), higher average percentage ground cover and higher variability in cover (i.e. greater pattern diversity) than sites close to water (Fisher, 1996).

Studies outside Australia. The effect of grazing by domestic stock on plant communities in arid and semi-arid zones has received considerable attention, particularly in North America and Africa. Many general patterns of change parallel those for Australian ecosystems discussed above. For example, the development of a denuded zone in the immediate vicinity of a watering point which is dominated by unpalatable, trample-resistant increaser species has been documented by Barker *et al*. (1989), Perkins & Thomas (1993*a*,*b*), Thrash (1998), Van Rooyen *et al*. (1990) and Zumer-Linder (1976) in Africa, Fusco *et al*. (1995) in North America and Adámoli *et al*. (1990) in Argentina. In the same studies, the abundance of palatable grasses increased and unpalatable species decreased with increasing distance from water. Another general trend on grazed landscapes is for the invasion of grasslands by unpalatable, perennial shrubs (e.g. Adámoli *et al*. (1990) for the Chaco of Argentina; Hennessy *et al*. (1983) for the Chihuahuan Desert, North America; Jeltsch *et al*. (1997) for Africa; Movia *et al*. (1987) for Patagonia). It is believed that grazing contributes to the initiation of this trend but lowering grazing pressure does not necessarily result in a reversal of the trend (Smith & Schmutz, 1975; Laycock, 1991).

While the release of sites from grazing by domestic stock does not lead to a reduction of perennial woody shrubs where they have come to dominate, changes in the assemblage of annual species after grazing has been removed can be substantial. Waser & Price (1981) recorded continual increases in species diversity of annual plants for 16 years after release from grazing in a Sonoran Desert grassland. In contrast, Kelt & Valone (1995) found no differences in species richness and only some species with higher abundance on sites that had been free of grazing by cattle for 16 years in the Chihuahuan Desert. Finally, Bock *et al*. (1984) found significantly more grass and herb cover, more abundant woody plants and little change in species composition in a livestock exclosure than on adjacent grazed land in a semi-desert grassland in Arizona.

Thrash *et al*. (1991*a*,*b*) and Thrash (1998) documented logarithmic curves of changing basal cover of grasses, forbs and woody vegetation on linear gradients away from bores in the Kruger National Park. While the measurable effects of grazing around artificial water points were only evident for a few kilometres, they drew attention to the loss of habitat diversity at greater distances due to the increased density of water points, hence the increase in the amount of area that is available to grazing animals during the dry season.

Van Rooyen *et al.* (1990, 1994) and Fourie *et al.* (1987) found that while grazing intensity had a significant effect on species composition of some habitat types in the southern Kalahari, it was not driven by a simple distance-from-water variable. Spacing of artificial sources of water in the Kalahari Gemsbok National Park is reported to be 6–18 km (mean = 12·4 km) with no serious degradation in zones closer to watering points (Van Rooyen *et al.*, 1994).

In the Sahelian region of Africa, the drilling of bores at regular intervals has led to widespread changes in the vegetation (Rapp, 1976; Glantz, 1977). Traditionally, heavy grazing during the dry season resulted in areas of denudation up to about 30 km from a well, but wells were spaced at large intervals so most of the land was ungrazed. With bores now at less than 30 km intervals most of the land area is denuded by the end of the dry season (Glantz, 1977). Rapp (1976) reported that cattle grazing around artificial sources of water in northern Sudan has resulted in the denudation of vegetation and soil compaction over areas of up to 10 km diameter. The regular removal of vegetation over large areas around artificial sources of water in these areas in Africa has led to another parallel with Australian rangelands: that is, the tendency for the development of a thick band of unpalatable shrubs at distances beyond about 1 km (Martens, 1971). The density of shrubs and spatial extent of the zone around a water point seem to depend on the duration and intensity of use of the area for grazing, as well as harvesting of firewood, a factor not common in Australia.

Effects of grazing on vertebrates

Studies of the impact of grazing by domestic stock on native animals have been conducted on all major terrestrial animal groups, mostly in North America. Many of these studies have compared populations of reptiles, birds and small mammals in grazed *vs.* ungrazed plots without replication.

Reptiles. Smith *et al.* (1996) examined the effects of sheep grazing on the lizard fauna of remnant woodland habitats in the semi-arid wheat belt of Western Australia and found no effect of grazing on species richness. Fisher (1996) found a weak trend of increasing reptile species richness with increasing distance from artificial sources of water in Mitchell grasslands. No reptile species are known to have become extinct in the arid and semi-arid zones of Australia (Sadlier & Pressey, 1994), and few of the species currently listed as endangered or threatened are found in arid and semi-arid pastoral zones (Cogger *et al.*, 1993). However, some species may be disadvantaged by pastoral activities. For example, the scincid species *Morethia boulengeri* and *Ctenotus regius* are associated with shrub leaf litter in western New South Wales (Henle, 1989) and where heavy grazing removes such accumulations these species may be locally absent (James, unpublished data).

Published studies from North American deserts all have concluded that grazing significantly decreases abundance of reptiles, but only sometimes affects species richness (Busack & Bury, 1974; Jones, 1981; Bock *et al.*, 1990). Changes in species composition or richness, when they occur, are attributed to structural changes in the habitat associated with grazed *vs.* ungrazed areas (Jones, 1981).

Birds. Species that have changed in abundance or range in arid and semi-arid Australia are identified in Table 1. Most authors attribute declines in the geographic range of birds to habitat change due to grazing. Birds of riparian and chenopod habitats have declined most significantly; overgrazing was identified as a likely cause because canopy-dwelling species have been less affected than ground-dwellers (Reid & Fleming, 1992). However, in mallee habitat where most of the species of birds dwell in the canopy 3–8 m above the ground, Williams & Wells (1986) found birds were less abundant in grazed areas (with water) than in ungrazed areas where water was also present.

In North American arid regions, the abundance of some bird groups is greater in the presence of grazing (Bock & Webb, 1984; Baker & Guthery, 1990) but lower in others (Bock *et al*., 1984; Knopf *et al*., 1988). Other studies have found an overall decrease in species richness associated with grazing (Taylor, 1986), no differences between grazed and ungrazed plots (Medin, 1986), or higher species richness associated with grazed plots (Medin & Clary, 1990). These differences are generally explicable by the habitat preferences of the species and the particular change in vegetational architecture that grazing causes (Ryder, 1980; Taylor, 1986). For example, grazing apparently creates suitable areas of open ground for grasshopper sparrows (*Ammodramus savannarum*) in some regions but destroys these habitats in the grasslands of south-eastern Arizona (Bock & Webb, 1984).

Mammals. Most species of medium-sized mammals found in semi-arid and arid pastoral lands of Australia (i.e. excluding macropods) have fared poorly since settlement by Europeans. Several reviews of past and present mammalian fauna in arid and semi-arid zones are summarized in Table 2. All emphasize that extinctions have been numerous and that most extinctions are among mammals of 'intermediate' body size (35–5500 g) (Burbidge & McKenzie, 1989). These reviews also show that extinctions have been equally as common in non-pastoral land as pastoral. For example, the region on which Boscacci *et al*. (1987) report has been grazed by sheep only since the 1950s and many of the mammals that occupied this region declined before pastoralism began. Thus, while some species were undoubtedly disadvantaged by habitat change associated with domestic stock in the first few decades after the advent of pastoralism, agents other than grazing were working in concert, including grazing by feral animals, particularly rabbits, and introduced predators (Morton, 1990; Smith & Quin, 1996).

Grazing by domestic stock in arid and semi-arid regions of North America has not been associated with the extinction of large numbers of native mammals as it has been in Australia. The abundance of small, ground-dwelling mammals in North America is generally greater on ungrazed plots than on grazed plots (Hanley & Page, 1981; Bock *et al*., 1984; Bowland & Perrin, 1989; Medin & Clary, 1989; Putman *et al*., 1989; Heske & Campbell, 1991). However, in one study of a seasonally grazed riparian habitat, abundance of small mammals increased under grazing (Medin & Clary, 1990). As with birds, some species responded positively to grazing while other species did not (e.g. Bock *et al*., 1984). Species richness was either not affected or was lowered by grazing (Medin & Clary, 1989, 1990; Putman *et al*., 1989).

Effects of grazing on invertebrates

The studies that have been conducted on invertebrates in arid and semi-arid areas of Australia indicate complex responses to grazing: abundance, species composition and richness respond in different ways depending on the taxonomic level (down to species), the season of sampling, the nature of changes to the architecture of the habitat and species composition of vegetation that result from grazing. Results for various groups of invertebrates are discussed below, integrating both Australian and overseas studies from a range of environments.

In North America, several studies indicate that grasshoppers can be more abundant on heavily grazed areas than on lightly grazed areas (Smith, 1940; Campbell *et al*.,

Table 1. *Changes in abundance and distribution of native species of birds in arid and semi-arid rangelands attributed to the effect of the provision of artificial water or pastoralism. Sources: 1 = Ford, 1961; 2 = Davies, 1969; 3 = Davies, 1972; 4 = Davies, 1977; 5 = Harrington* et al.*, 1988; 6 = Curry & Hacker, 1990; 7 = Saunders & Curry, 1990; 8 = Reid & Fleming, 1992; 9 = Smith & Smith, 1994; 10 = Smith* et al.*, 1994. Habitat notes were taken from the Birds Australia database*

Response	Species	Habitat	Source
Extinct in many regions	Black Bittern	Aquatic vegetation	9,10
	Lewin's Rail	Aquatic vegetation	9,10
	Little Wattlebird	Heath	9,10
	Malleefowl	Mallee	6,7,8,10
	Night Parrot	*Spinifex*, Chenopod	6,8
	Regent Honeyeater	Temperate forest	9,10
	Scarlet-chested Parrot	Spinifex, *Acacia* scrub, Mallee	6,8
	Thick-billed Grasswren	Chenopod	6,8,9,10
Lowered abundance and/or reduced range	Alexandra's Parrot	Spinifex, *Acacia* scrub	6
	Barking Owl	Woodland	8
	Black-breasted Buzzard	Grassland, Spinifex, *Acacia* scrub, Chenopod	8,9,10
	Black-chinned Honeyeater	Spinifex, *Acacia* scrub	8
	Brolga	Grassland, aquatic vegetation	8
	Bush Thick-knee	Grassland, Chenopod	8,9,10
	Channel-billed Cuckoo	Woodland	8
	Chestnut Quail-thrush	Spinifex, *Acacia* scrub, Mallee	8
	Chestnut-breasted Quail-thrush	Spinifex, *Acacia* scrub, Chenopod	8
	Chiming Wedgebill	Spinifex, *Acacia* scrub, Chenopod, Mallee	8
	Cinnamon Quail-thrush	*Acacia* scrub, Chenopod	8
	Dusky Grasswren	Spinifex	8
	Eastern Grass Owl	Grassland	8
	Eyrean Grasswren	Grassland	8
	Flock Bronzewing	Grassland, Spinifex, Chenopod	6,8,9,10
	Grey Currawong	Heath, Mallee	7,8
	Grey Grasswren	Grassland, Chenopod	8
	Grey Honeyeater	*Acacia* scrub	8
	Hall's Babbler	*Acacia* scrub	8
	Letter-winged Kite	Grassland, *Acacia* scrub	8,9,10
	Little Button-quail	Grassland, Spinifex, *Acacia* scrub	7,8
	Magpie Goose	Grassland, Aquatic vegetation	8,9,10
	Masked Owl	Woodland	9,10
	Nullarbor Quail-thrush	Chenopod	6
	Peregrine Falcon	Heath, Spinifex	8
	Pheasant Coucal	Grassland, heath	6,8

Table 1—*continued*

Response	Species	Habitat	Source
	Pied Honeyeater	Spinifex, *Acacia* scrub, Mallee	8
	Pink Cockatoo	Grassland, *Acacia* scrub, Mallee	8
	Plains-wanderer	Grassland	5,9,10
	Purple-crowned Lorikeet	Mallee	9,10
	Red-browed Pardalote	Spinifex, *Acacia* scrub	8
	Red-winged Parrot	*Acacia* scrub	8
	Redthroat	Spinifex, *Acacia* scrub, Chenopod	8
	Rufous Field-wren	Heath, Chenopod, Mallee	6,7,8
	Squatter Pigeon	*Acacia* scrub	9,10
	Striated Grasswren	Spinifex, Mallee	9,10
	Tawny-crowned Honeyeater	Heath, Mallee	9,10
	White-fronted Chat	Grassland, heath, Chenopod	7
	White-winged Fairy-wren	Spinifex	6,7,8
Increased abundance and/or enlarged range	Australian Crake	Aquatic vegetation	6
	Australian Kestrel	Grassland, heath, Spinifex, *Acacia* scrub	8
	Australian Magpie	*Acacia* scrub, Mallee	8
	Australian Magpie-Lark	Grassland, *Acacia* scrub, Chenopod, Mallee	6,7,8
	Australian Pratincole	Grassland	8
	Australian Raven	Grassland, heath, Spinifex, *Acacia* scrub	8
	Banded Lapwing	Grassland, Chenopod	6,7,8
	Banded Whiteface	Spinifex, *Acacia* scrub, Chenopod	6,7,8,10
	Bar-shouldered Dove	*Acacia* scrub	9,10
	Black Kite	Grassland, Spinifex	8
	Black-faced Woodswallow	Spinifex, *Acacia* scrub, Chenopod	7,8
	Black-shouldered Kite	Grassland	8
	Bourke's Parrot	*Acacia* scrub	1,4,6,7,8,10
	Brown Honeyeater	Heath	8
	Brown Songlark	Grassland, Spinifex, *Acacia* scrub	8
	Cattle Egret	Grassland	9,10
	Common Bronzewing	Heath, *Acacia* scrub, Chenopod, Mallee	6,8
	Crested Pigeon	Grassland, Chenopod, Mallee	1,6,7,8
	Fairy Martin	Grassland	8
	Galah	Grassland, heath, Spinifex, *Acacia* scrub	1,6,7,8

Table 1—*continued*

Response	Species	Habitat	Source
	Grey Butcherbird	Grassland	8
	Grey-crowned Babbler	*Acacia* scrub	6,7,8
	Inland Dotterel	Grassland, Chenopod	6,7,8
	Little Corella	*Acacia* scrub	8,10
	Little Crow	Grassland, Spinifex, *Acacia* scrub, Chenopod	7,8
	Little Egret	Aquatic vegetation	9,10
	Mallee Ringneck	*Acacia* scrub, Mallee	6,8
	Peaceful Dove	*Acacia* scrub	8
	Pied Butcherbird	*Acacia* scrub, Chenopod, Mallee	7,8
	Red-rumped Parrot	*Acacia* scrub	8
	Richard's Pipit	Grassland, Spinifex, Chenopod	8
	Rufous Songlark	Grassland, Spinifex, *Acacia* scrub	8
	Southern Whiteface	Spinifex, *Acacia* scrub, Mallee	8
	Spiny-cheeked Honeyeater	Spinifex, *Acacia* scrub, Mallee	7,8
	Spotless Crake	Grassland, aquatic vegetation	6
	Striated Pardalote	Mallee	8
	Superb Fairy-wren	Grassland, heath	10
	Torresian Crow	*Acacia* scrub, Chenopod, Mallee	7,8
	Welcome Swallow	Grassland, heath, *Acacia* scrub	6,7,8
	Western Bowerbird	*Acacia* scrub	6,7,8
	White-backed Swallow	Grassland, *Acacia* scrub, Chenopod, Mallee	8
	White-breasted Woodswallow	Grassland, *Acacia* scrub, Chenopod	8
	White-plumed Honeyeater	Woodland, Mallee	8
	Willie Wagtail	Grassland, heath, *Acacia* scrub, Chenopod	8
	Yellow-rumped Thornbill	Grassland, Spinifex, *Acacia* scrub, Chenopod	6,7,8
	Yellow-throated Miner	Heath, Mallee	8
	Zebra Finch	Grassland, Spinifex, *Acacia* scrub, Chenopod	1,6,7,8
Abundance has increased in some areas and decreased in others	Emu	Grassland, heath, Spinifex, *Acacia* scrub	2,3,6,7,8,10
	Plumed Whistling-Duck	Grassland	8,9,10
	Red-tailed Black-Cockatoo	Woodland, Grassland, *Acacia* scrub	7,8
	Spinifex Pigeon	Spinifex, *Acacia* scrub	6,8,10
	Wedge-tailed Eagle	Grassland, heath, Spinifex, *Acacia* scrub	6,7,8

Table 2. *Published literature on changes in the species richness of mammalian fauna in Australia from pre-European settlement to present day*

Region	Past number*	% lost†	Source
Arid zone	46 spp. marsupials	30	Aslin, 1983
Arid zone (central and western)	Rodents	44	Morton & Bayne, 1985
	Polyprotodont marsupials	41	
Nullarbor plain	23 spp. ground mammals	43	Boscacci *et al.*, 1987
Simpson Desert		31	Gibson & Cole, 1988
Arid Western Australia (pastoral and desert zones in Fig. 1 of Burbidge & McKenzie)	51 spp. pastoral, non-volant	27·5	Burbidge & McKenzie, 1989
	41 spp. desert, non-volant	39	
	63 spp. all arid zone, non-volant	28·6	
Arid north-western South Australia		53·5	Copley *et al.*, 1989
Arid north-western Victoria		27·3	Robertson *et al.*, 1989
Arid western half of continent	70 spp. all ground mammals	56% rodents 59% marsupials	Curry & Hacker, 1990
Uluru National Park	76 spp. all ground mammals	25	Baynes & Baird, 1992
	12 spp. bats	8·3	
Arid and semi-arid western New South Wales	71 spp. all mammals	38	Dickman *et al.*, 1993

* Presumed species richness of fauna prior to European settlement from early records and/or sub-fossil deposits.
† Refers to probable extinction from the region under study.

1974; Holmes *et al.*, 1979), or the reverse (Miller & Onsager, 1991; Fielding & Brusven, 1995). These discrepancies usually result from one or two species that are highly favoured by heavy grazing (some Oedipodinae) becoming superabundant in overgrazed rangeland (Smith, 1940; Capinera & Sechrist, 1982; Denny, 1983). Other taxa, such as most species of Melanoplinae, are more abundant on lightly grazed sites (Holmes *et al.*, 1979; Capinera & Sechrist, 1982; Quinn & Walgenbach, 1990; Fielding & Brusven, 1995). Trends in abundance also change with season: Jepson-Innes & Bock (1989) found grasshoppers to be 3·7 times more abundant on an ungrazed exclosure in a gramma (*Bouteloua* sp.) grassland of southern Arizona than on nearby grazed sites during summer, but the situation reversed in autumn. In a more detailed study of changes in grasshopper species composition under grazing, Quinn & Walgenbach (1990) found complex changes in abundance and composition due to a high degree of feeding specificity among species of different sub-families of grasshoppers. Overall, there was a correlation between species richness of grasshoppers and the species richness and cover of vegetation (Quinn & Walgenbach, 1990).

Ants are a good indicator taxa of disturbance (Andersen, 1990) but their use in assessing or monitoring grazing effects in rangelands is still in its infancy. Abundance and species richness show a range of responses under grazing (Putman *et al.*, 1989; Heske & Campbell, 1991; Abensperg-Traun *et al.*, 1996). A promising avenue of analysis is examination of changing species composition in relation to functional groups. Bestelmyer & Wiens (1996) showed that different functional groups of ants dominated under different grazing regimes, whereas Abensperg-Traun *et al.* (1996) found that only opportunists (see Andersen, 1990) were significantly different in species richness between areas with different grazing regimes.

One study of the effect of grazing on scarabaeid beetles has shown little or no effect on abundance or species richness (Jameson, 1989), whereas another study found that staphylinids were more abundant and carabids less abundant on grazed sites (Putman *et al.*, 1989). Abensperg-Traun *et al.* (1996) found increasing abundance and species richness of curculionids (weevils), and increasing abundance of carabids, from low to high grazing.

Spiders show significant differences in abundance and species richness between areas with different grazing intensities, but responses vary among families. Gibson *et al.* (1992), working in a grassland in the United Kingdom, found species richness and abundance decreased with increasing grazing intensity: heavily grazed areas were dominated by Linyphiidae; large web-spinners were most affected by higher grazing intensity; and the effects of grazing could be best explained through its effect on vegetative architecture on which spiders rely for webs. Abensperg-Traun *et al.* (1996) found highly significant changes in the abundance of spiders of different families, but the direction of the trend (positive, negative, humped) differed among families.

Responses to grazing were also varied among other epigaeic fauna studied by Abensperg-Traun *et al.* (1996). Isopods and blattids were more abundant and species rich at intermediate levels of grazing, and scorpions declined in abundance and species richness with increasing grazing intensity.

Little is known about the effect of grazing on invertebrates which occur predominantly below-ground. For termites, grazing has been shown to have no effect on the species richness of the assemblage, but to increase mound density in one study (Abensperg-Traun, 1992), and to lower the abundance of harvesters in another study (Abensperg-Traun *et al.*, 1996) in semi-arid woodland habitats in Australia. In other studies in Australia, low to moderate levels of grazing seem to benefit termite populations (Watson *et al.*, 1973; Braithwaite *et al.*, 1988). This may be because termites have higher reproductive output when more nutrients are available in food plants (Lenz, 1994). Weir (1971) suggested that the herbivore dung that accumulates near watering points may facilitate an increase in the abundance of termites because dung is a food resource for some termites.

Other below-ground taxa to have been studied are Collembola and Cicadidae (Hemiptera). Surface-dwelling Collembola decreased in species richness under heavy grazing pressure but Collembola living deep in the soil did not react as strongly (Hutchinson & King, 1970; King *et al*., 1976). Subterranean larval stages of cicadas were lower on degraded rangeland (Milton & Dean, 1992) where the reduction was attributed to the removal of perennial plant cover by overgrazing.

Effects of artificial water points as a source of drinking water

Australian native mammals—kangaroos and wallabies

Kangaroos and wallabies graze native grasses and perennial vegetation. Prior to European settlement, the larger, water-dependent species were probably found in riparian areas and around a few scattered natural waterholes most of the time; that is when forage was dry and water unavailable across most of the landscape. After good rainfalls, when green forage and free water were available, populations would have built up and expanded into the surrounding country (Ealey, 1967). As the next dry spell returned, populations would decline and contract toward permanent waterholes.

Since European settlement, the large kangaroos have prospered: large populations of red, eastern grey and western grey kangaroos, and wallaroos are present in most pastoral regions (Main *et al*. 1959; Frith, 1964; Ealey, 1967; Calaby, 1971; Doohan, 1971; Newsome, 1971, 1975; Cunningham, 1981; Denny, 1985; Norbury, 1992). It is difficult to judge the population sizes of kangaroos prior to the advent of the pastoral industry because the records in explorers' diaries are unreliable (Noble & Tongway, 1983*a*). Nevertheless, it is widely accepted that artificial sources of water and the removal of the dingo help maintain larger populations of kangaroos in pastoral areas than would have been possible in the past.

Kangaroos are most numerous around artificial sources of water, particularly during dry summer periods and drought (Newsome, 1965; Norbury & Norbury, 1993; Gibson, 1995). Kangaroos require most water in summer for thermoregulation (Dawson *et al*., 1975), and closing artificial sources of water results in local declines in kangaroo abundance (Gibson, 1995).

Other native Australian animals—birds

A number of bird species have expanded their geographic ranges or increased in abundance because of the provision of artificial sources of water, for example, crested pigeon (*Ocyphaps lophotes*), zebra finch (*Taeniopygia guttata*) and galah (*Cacatua roseicapilla*) (Table 1). Fisher *et al*. (1972) concluded that 71 of 118 species studied on 18 sites across the arid and semi-arid zones of Australia were either independent of water, were never observed drinking, or drank less than 50% of the time. They also found, however, that the majority of individuals inhabiting areas where water is present (developed pastoral land) were dependent on free water, and its availability was a critical factor in the distribution of those species. Prior to the provision of artificial sources of water, species that are dependent on free water could only inhabit arid areas around permanent natural water, and over larger areas following good falls of rain (Fisher *et al*., 1972; Davies, 1977).

Williams & Wells (1986) found that the presence of water (independent of grazing) facilitated larger populations of birds in all seasons except spring in a mallee habitat in South Australia. Species richness was also higher on transects with artificial sources of water than transects without. Artificial sources of water were also found to affect the distribution and abundance of birds in Mitchell grasslands: five water-dependent species, or those that preferred open areas, were more abundant within 5 km of water points (Fisher, 1996).

Some of the bird species that have become abundant may cause competitive or aggressive displacement of other species that do not need water. For example, yellow-throated miners (*Manorina flavigula*) may be resulting in the local displacement of some small birds (Grey, 1996). Similar competitive or aggressive displacement interactions may be occurring among other species of birds but there have been no studies of this topic of which we are aware.

Non-native Australian animals—feral herbivores

In Australia, a range of introduced, feral, large mammalian herbivores use artificial sources of water for drinking and therefore add to the total grazing pressure. Some of these are low in abundance and their effect may be trivial compared to that of domestic stock (and kangaroos), but others such as feral goats can be as abundant as domestic sheep and therefore are a major component of the grazing pressure.

The feral goat population in Australia in 1993 was estimated to be 2·6 million (Parkes *et al*., 1996), most of them occurring in the semi-arid rangelands. Goats need to drink during hot or dry periods and so only occur where natural or artificial sources of water are available; they are particularly abundant in areas where shrub cover is available and dingos have been removed (Southwell *et al*., 1993). In areas such as northern New South Wales and central southern Western Australia, goats (and kangaroos) are estimated to be as numerous as sheep (Freudenberger, 1993; Landsberg & Stol, 1996). Superficially, the direct and indirect changes to vegetation and fauna attributable to grazing by sheep can also be attributed to grazing by goats. But goats can move through wire fences designed to constrain the movement of sheep and so can access preferred vegetation independent of paddock boundaries. Goats also eat a greater range of plants than sheep (Dawson *et al*., 1975; Harrington, 1979) and this may allow them to maintain populations longer than sheep during dry periods, with a coincident damage to the habitat.

Estimates of the feral horse population in Australia range from 300–600,000 individuals (Berman & Jarman, 1987)—the largest wild population in the world. Horses require drinking water regularly and prefer more nutritious feed than cattle. In central Australia, horses graze flood plain and riparian habitat after rain when palatable plants are available. As the forage dries, horses move into rocky country to obtain nutritious feed (Berman & Jarman, 1987). They can travel further than cattle to water and so can move to areas where feed is more plentiful between drinks (Low, 1974; Berman & Jarman, 1987). Horses add to grazing pressure and help denude areas of vegetation during dry periods and accelerate gully erosion. They also degrade wildlife refuge areas in the central Australian mountain ranges by fouling natural waterholes and drinking small waterholes dry (Dobbie *et al*., 1993).

The feral camel population in Australia is the largest wild population in the world, estimated to be around 100,000 individuals (Camel Industry Steering Committee, 1993). Camels live mostly in desert country on the fringe of pastoral settlements. They are independent of drinking water during periods when forage is green but do come through fencelines to drink at artificial sources of water during dry periods (McKnight, 1969; Newsome & Corbett, 1977; Dörges & Heucke, 1996). Camels eat a range of tree and shrub foliage and grasses. At densities of 10–20 km^2 per animal in central Australia, feral camels apparently do little damage to vegetation or watering points (Dörges & Heucke, 1996).

Pigs (*Sus scrofa*) utilize wetland habitats around free flowing bores or natural wetland areas often associated with earth dams. They are the only feral species in Australia to require wetland areas for a habitat; all other feral mammals use artificial sources of water primarily for drinking. They eat green grasses, roots, carrion and occasionally kill lambs. Populations densities have been recorded as high as 80 per km^2 in the Macquarie Marshes and 20 per km^2 near a stock watering point in north-west New South Wales (Giles, 1978). With such large population densities they can do considerable damage to vegetation while foraging. While their effect on native animals is unreported, they can presumably kill and eat animals up to the size of lambs.

Rabbits (*Oryctolagus cuniculus*) get the water they need from forage most of the time, but occasionally they are observed drinking at artificial sources of water (Cooke, 1982). This probably occurs when the forage is too dry or too scarce to provide the necessary water. This situation is rare and the effects of rabbits on native vegetation (which are substantial, e.g. Newsome & Corbett, 1977) are usually associated with a grazing halo around warrens rather than from artificial sources of water.

Animals in other countries

Artificial sources of water are a focus for drinking by native animals and domestic stock in arid and semi-arid regions around the world. In regions such as southern Africa, a high diversity of native mammals use artificial water points for both drinking water and mineral salts present in water (Knight, 1989). Many of their effects are similar to those of domestic stock, in particular grazing, trampling and defecation (discussed in other sections). The direct effects of the provision of artificial sources of water for game in southern Africa are probably complex because of species interactions, but some simple effects are that common water-dependent species become numerous at the expense of other species, and predators may be advantaged (Owen-Smith, 1996). A detailed discussion of this topic is beyond the scope of this review; however, we will mention a few pertinent examples. In Kruger National Park, the extensive provision of artificial sources of water has led to substantial increases in the populations of water-dependent herbivores (e.g. zebra and wildebeest) and lions because of the availability of prey, a reduction in the populations of water-independent species (e.g. roan antelope), and heavy concentrations of animals within a few kilometres of water (Thrash *et al*., 1995; Owen-Smith, 1996; Thrash, 1998). In contrast, Van Der Walt (1986) found that only springbok (*Antidorcas marsupialis*) and blue wildebeests (*Connochaetes taurinus*) showed a preference for habitat around water in the Kalahari Gemsbok National Park, mainly during winter. They concluded that the provision of artificial sources of water had little effect on the natural patterns of habitat use by large herbivorous mammals. Finally, Western (1975) studied the distribution and abundance of 15 species around natural and artificial sources of water in the Amboseli basin on the border of Kenya and Tanzania. Western found that water-dependent mammals were concentrated within 10 km of water during the dry season, whereas species not dependent on water were distributed reasonably uniformly up to 35 km from a water point. The biomass of water-dependent species (including stock) within 10 km of water was of the order of 10 times that of water-independent species within the same radius, or water-dependent species beyond 10 km. Thus, the concentration of wild and domestic animals at water points during a few dry months of the year creates a large imbalance in the distribution of grazing intensity.

Habitat for native flora and fauna

Some free-flowing artesian bores in South Australia and parts of Queensland have produced localized wetlands which have developed into habitats of major significance for biota, particularly birds. Badman (1987) surveyed 171 bores in north-eastern South Australia and concluded that 22 of them were significant enough to warrant conservation effort. These artificial wetlands are similar in species composition to the natural ones that developed along the south-western edge of the Great Artesian Basin (e.g. Dalhousie Springs; Fig. 1(d)). There is usually a central core of reeds (*Typha* and *Phragmites* spp.) surrounded by mudflats, often with *Halosarcia* spp. Beyond that, there can be a fringe of shrubs of *Acacia* spp., chenopod shrubs and *Nitraria* spp. Where water follows a creek line, a eucalypt woodland may be maintained.

Badman (1987) indicated that the artificial wetlands support a large number of species of birds that otherwise would not occur in the arid north-eastern corner of South Australia. However, if the wetlands were to be removed, only one species (the brolga, *Grus rubicundus*) might disappear from South Australia; the rest would persist in other areas or at lower densities.

Artificial sources of water in the form of wetlands, dams or tanks may also provide habitat for a range of aquatic or semi-aquatic species. Weir (1971) suggested that permanent water supplied to claypans from bores in the Hwange National Park, Zimbabwe, has disadvantaged crustaceans, Conchostraca and Anostraca which were adapted to the wet–dry seasonal flooding of claypans. Other taxa that rely on water for habitat or to complete a life cycle, such as dragonflies (Odonata), may have increased their range or duration of occupancy in a region because of artificial sources of water (Weir, 1971). This could also be true for many taxa of invertebrates in Australia, but has not been studied.

Effects of artificial water points as a focus for hunting and drinking by predators

As a direct result of native species using artificial sources of water to drink, predators converge on water to drink and hunt. The problems that this causes in Africa have been noted above (see Owen-Smith, 1996). Predators commonly seen at watering points in Australia are cats (*Felis catus*), foxes (*Vulpes vulpes*) and dingos (*Canis lupus dingo*). Cats and foxes have been introduced into Australia since European contact and have spread over most of the continent (Strahan, 1995). Dingos were introduced to Australia by Aborigines, probably around 3500 years ago (Corbett, 1995). They have been greatly reduced in abundance and range since pastoral settlement because they kill sheep, and are controlled by fencing (Fig. 1(a)), shooting and baiting.

There appears to be no published information documenting how many animals these predators kill at watering points in arid environments. Cats derive most of their water needs from live prey and probably do not need to drink except during very hot dry periods when live prey are sparse (G. Edwards, pers. comm.). Dingos and foxes do need to drink regularly in hot weather (Newsome & Coman, 1989); thus, populations are probably greater, and maintained over a larger area, than would be possible without artificial sources of water (Newsome & Corbett, 1977). Cats may be present around watering points primarily to hunt, whereas dingos and foxes are there to drink, scavenge dead stock and hunt.

There is no published information on the types of prey most frequently captured at artificial sources of water, but birds are a likely target (Jones & Coman, 1981; Catling, 1988). Birds constitute a greater proportion of the diet of cats living in an arid environment than they do in more mesic environments (Jones & Coman, 1981), perhaps because cats focus their activity on watering points, where birds are common. The diet of foxes from arid areas is mostly mammalian carrion but birds, reptiles and amphibians are also eaten (Martensz, 1971). Presumably amphibians and some birds may be taken near artificial sources of water such as dams. Dingos prey on kangaroos around watering points, and they are major regulators of kangaroo populations in eastern Australia (Caughley *et al*., 1987). Carcasses of cattle and sheep around watering points during drought help maintain populations of dingos and foxes.

Little is known of the direct effect of these predators on biodiversity, although cats and foxes have been implicated in the extinction or near extinction of many medium-sized native mammals in Australia such as the desert bandicoot (Peramelidae: *Perameles eremiana*), burrowing bettong (Potoridae: *Bettongia lesueur*) and the lesser stick-nest rat (Muridae: *Leporillus apicalis*) (Kinnear *et al*., 1988; Morton, 1990; Smith & Quin, 1996; Short, 1998).

Concluding remarks

Artificial sources of water have primarily been developed to maintain populations of large herbivores in arid areas for commercial production of domestic stock or for sightseeing value. The number and spacing of artificial sources of water across the arid and semi-arid zones fundamentally alters the character of the landscape. Native wild animal species that rely on drinking water, or water as a habitat for part of their life cycle, are able to persist in areas that were previously not habitable most of the time, resulting in larger and more widespread populations of these species than would otherwise be possible. In a number of cases, the increase in abundance of a species may have significant negative effects on other species.

Apart from these specific direct effects, artificial sources of water also maintain high levels of grazing pressure over very large areas. Plants and animals that are not directly affected by the presence of water are often affected by the presence of large numbers of grazing animals and the results of their grazing. Interpretation of patterns in species richness or diversity among samples from areas with different grazing regimes has been confounded by the diversity of responses from different species and the range of spatial scales measured.

The density of artificial sources of water across the arid and semi-arid rangelands of Australia (Landsberg & Gillieson, 1996) is such that moderate to heavy grazing is maintained over large areas. Similar extensive provision of artificial sources of water have occurred in many other arid and semi-arid zones around the world. This review has highlighted that there is generally a poor an appreciation of the multiple effects of the provision of water but that there are a few researchers and managers from different regions around the world raising strong concerns about the trend: Landsberg *et al*. (1997) in Australia; Belsky (1995), Thrash *et al*. (1995), Owen-Smith (1996) and Thrash (1998) in Africa; and Noy-Meir (1996) in eastern Europe. There appears to be a consistent message of warning coming from these different authors in different regions: widespread provision of artificial water in previously dry landscapes is potentially threatening to many species through many of the mechanisms identified in this paper.

The development of extensive commercial industries based on artificial sources of water in dry landscapes means that there is the potential for conflict between management for commercial interests and management that aims to conserve the range of native species from a region. If the second of these aims is to be the objective, then we have to acknowledge that the conservation of all species is not compatible with uniform heavy grazing across whole landscapes. Plans for the management of rangelands for both grazing and conservation could either: (1) consider each species individually and tailor management of specific areas for that species; or (2) determine general suites of organisms with similar responses and develop management strategies that maintain patchiness so that most species are able to find some part of the landscape that is suitable for persistence. We believe the second method is most pragmatic. This view requires recognition that a proportion of species found across a region can exist in highly disturbed, heavily grazed areas near water points; that other species will require virtually ungrazed areas for long-term persistence; and that the remainder probably require varying degrees of conditions in between. While pastoralism in rangelands is essential for the livelihood of many people worldwide there will always be an abundance of areas close to watering points. The management challenge is to develop a balanced representation of areas and habitats across the landscape that are influenced to different degrees by water sources, so that the requirements of all species are accommodated. Water points are a powerful tool for controlling activity and grazing by large herbivorous mammals, and therefore they are a potentially powerful tool for managing conservation of biodiversity in arid and semi-arid zones.

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