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Australian Earthworms as a Natural Agroecological Resource

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Abstract: Australia has an unrealized natural resource in its unprecedented diversity of earthworms. Surveys on the ground and of the literature give a total for Australia (and Tasmania) of 715 species and sub-species in 73 genera and ten families, comprising 650 endemic natives, wholly adapted to Australian climates and soils, and 65 (ca. 9%) exotic interlopers that tend to be less specialized, but more widespread. Of the exotics, just one-third, about 3% of the total species, are lumbricids of the holarctic family Lumbricidae. If neo-endemics and translocated natives are included as non-natives, it raises their numbers above 80 species – higher than a previous "National Survey" estimate of just 27 species. Compared to any other region, the earthworm fauna of Australia is particularly diverse (e.g. India – 350 spp., New Zealand – 200 spp.; USA/Canada – 180 spp.; USSR – 113 spp.; Amazonia – >120 spp; British Isles ca. 69 spp.) and, as much of the continent has yet to be systematically surveyed, it is anticipated that the tally of both natives and exotics will continue to grow many-fold. Earthworms are vital for sustainable primary production and waste management, yet only slowly do we gain an ecological appreciation of their potential to benefit Australia's natural environment. Experiments and field trials in Australia have tended to mimic those conducted overseas, especially in Europe, using a limited range of exotic species, with similarly variable results and have largely overlooked native species. A long-term project to import the exotic *Aporrectodea longa* from Tasmania to the mainland was somewhat compromised from the outset by the well-documented prior occurrence, not only of this species, but also of many other 'deep-burrowing' species, on the mainland. However, it now seems that modifying soil to maintain or enhance conditions favorable for resident populations to recolonize and expand may prove the most beneficial option for both worm and farmer. Appropriate management strategies are briefly presented.

Key words: Australian earthworm biodiversity, natives, exotics, soil management.

Soil is not, then, something that is dead. It is teeming with a great variety of life forms ranging in size from the submicroscopic viruses, through bacteria, microbes, fungi, to the colossus of the various species of earthworms. A mere handful of warm, moist, fertile soil contains a life population that is astronomical P.A. Yeomans (1958): Keyline Plan.

Earthworms, or the often larger megadrile annelids of the class Oligochaeta, are ubiquitous and amongst the most ancient of terrestrial animal groups. They play a vital role in the formation and maintenance of fertile soils and are thus paramount for primary production (**Fig. 1**). Charles Darwin (1837; 1881) was one of the first scientists to give credence to the conventional wisdom from earlier civilizations about the importance of earthworms to soil fertility, and thus human survival. A resurgence in interest in earthworms is driven by

Fig. 1. Effects on plants (Sorghum bicolor) and soil two weeks after five earthworms (Pontoscolex coethrurus) added to core on right-hand-side compared to control. [Photo Courtesty of Dr. Les Robertson, BSES, Tully].

environmental and economic concerns, particularly the need to understand and utilize their function in sustainable agriculture, to exploit their potential for recycling organic matter and as indicator species for environmental health (Lee, 1985; Sims and Gerard, 1985, 1999; Buckerfield *et al.*, 1997; Paoletti, 1999; Blakemore, 2002).

Perhaps the most important functions attributed to soil biota are:

- maintenance of soil structure,
- regulation of nutrient cycling processes,
- direct interacting with plants and indirectly via microbial stimulation,
- as indicator species of the state of health of the soil ecosystem, and
- as alternative food source for insect biocontrol predators.
- as bioprospecting resources for new molecular or pharmaceutical products.

Earthworms are a major component of the soil macrofauna and as potential restorative agents or ecosystem engineers, have significance in all these processes and roles, either directly (e.g. by working the soil) or indirectly (e.g. by influencing macro-, meso-, and micro- organisms). The issues of soil physical properties, chemical fluxes, soil formation, plant production and decomposition, and soil biotic processes are all interrelated. The mechanisms and magnitudes of the contribution of earthworms are reviewed elsewhere, e.g. in Lee (1985), Blakemore and Temple-Smith (1996), and Edwards and Bohlen (1996).

Earthworm communities comprise four components (Blakemore, 1999; 2002): resident natives that are often highly endemic, translocated natives (i.e., endemics relocated within a bioregion), neoendemics (i.e., speciation in a new region after introduction), and introduced exotics that tend to be less specialized and more widespread. Recent studies have revealed a previously unrealized Australian biodiversity of each of these groups while also simplifying the taxonomic process, without sacrificing phylogenetic relationships, in order to relieve field taxonomists from the tedious requirements to obtain SEMs of modified setae (where present), or a futile hunt for obscure (and often absent) fine ultrastructural nephridial minutiae. Much more reliance and importance is placed on the condition of the less environmentally adaptive reproductive organs, internal and external structures define taxonomic groups and allow resolution at all levels for the majority of species (Blakemore, 2005).

The most important foundation of our understanding of species diversity comes from field observation and taxonomic surveys, for earthworms, as with other groups, the outcomes are dependent of two factors: reliability of sampling methods and competency of identification (**Table 1**). Too often soil faunal surveys do not adequately sample e.g., using narrow diameter corers, or Tullgren funnels that miss larger specimens, yet report earthworms as "negligible" or "depauperate"; and smaller species may easily be misidentified or classed as immature, whereas incomplete identifiers, with only a few choices, force just those choices. A solution is an "eco-taxonomic" methodology aimed at overcoming both these deficiencies, as advocated and explained by Blakemore (1994; 2000; 2002), ISO 23611-1 (2006) and ICZN (1999). In brief, this involves adequate and representative ecological sampling, combined with thorough taxonomic determination of collected materials (to Family, Genus, Species, Sub-species levels) (**Table 1**).

Compilation of Australian species mapped by Abbott (1994) showed most earthworms are reported from regions with >400 mm annual rainfall, exceptions are those from river basins such as the Murray-Darling (see Blakemore, 2000b). But this may be a partial artifact of sampling effort, as arid regions tend to be under-represented in surveys due to logistic constraints and infrequent favorable periods. Yet arid areas can support populations: sampling in temperatures >40°C, with soil so dry and hard that a pneumatic drill was required, Blakemore (1994; 1997a) discovered abundant natives, quiescent at depth under pasture in Queensland sub-tropics.

Table 1. Contingency table of sampling reliability

Case	Sampling	Taxonomy	Results
1	+	+	Representative data
2	+	–	Unrepresentative data
3	–	+	Unrepresentative data
4	–	–	Unrepresentative data

+, Good; -, Poor.

Methods and Presentation

Data herein is compiled from field and literature surveys extending over several years and from reviews such as those presented by Lee (1985), Edwards and Bohlen (1996) and citations in Blakemore (2005). The current paper will follow section headings in a chapter of the recent update of "Earthworm Ecology" by Baker (2004) titled "Managing Earthworms as a Resource in Australian Pastures" and offer responses to some issues raised therein.

The Earthworm Fauna in Australia

Under this heading Baker (2004) states "The earthworm fauna is dominated by exotic species, most notably Lumbricidae…introduced accidentally from Europe" and "Thus, the most common earthworm species in disturbed land in Australia are the peregrine lumbricid species.." These statements are misleading as, from a total Australian fauna now known to comprise 715 species, only about 65(9%) are exotics and, of these, only a third (or about 3% of the total) are from the holarctic family Lumbricidae. Possible reasons why these exotics are claimed to be dominant is due to lack of adequate sampling and/or identification skills as confirmed by quantitative and qualitative sampling in various regions of Australia, from sub-antarctic to sub-tropics, where lumbricids were found frequently, but as just a component, whether in managed or unmanaged habitats. These results are summarized in Blakemore (2005) where the 715 taxa in 73 genera and 9-10 families represent the most complete and comprehensive checklist of Australian earthworms. About 650 are natives in 45 genera in just 3 or 4 families plus 10 or 12 possible neo-endemics, fully adapted to Australian climates and soil conditions, and another 64-65 species are cosmopolitan exotics that often have broad tolerances and worldwide distributions (Blakemore, 2002). Of these exotics about 20 are new national or state records from the senior author's studies including the first Australian report of *Lumbricus terrestris* Linnaeus, 1758, but many of the new records are for smaller species.

These national figures naturally include the 230 native and exotic Tasmanian species in 38 genera belonging to 4 families comprising: 202 natives (in 24 genera), 1 new species (Blakemore unpublished) and 1 neo-endemic (from Subantarctic Macquarie Island), 3 translocated mainland species and 23 exotics that have several cosmopolitans in common with the mainland (Blakemore, 2000a,b,c; 2004). Both exotics and natives, e.g. several *Anisochaeta*, *Anisogaster* and *Megascolides* spp., were found on farms and under pasture.

Many more species await description, e.g. Abbott's (1985b) collection from the Jarrah forests of WA in the Museum of Natural History, London, number more than 60 morpho-species (pers. obs. RJB, 1996), and further field surveys and sifting through the shelves of Museum collections will undoubtedly reveal many new, undescribed species that will, naturally, not be listed anywhere and for which specialist help is needed. Thus it can be anticipated a total fauna for Australia to increase many fold to eventually number several thousand taxa.

Australia thus has a much greater natural resource base of earthworm species than available in most other regions of the Globe, and it is perhaps less appropriate to emulate studies from North America (that has less than 200 earthworm species in total - Blakemore, 2005) or Northern Europe e.g. British Isles with just 69 recorded species (although ca. 20 of these were from Botanic Gardens - see Blakemore, 2005), where climatic and edaphic conditions differ and the faunas are more limited. What is needed is an initiative to re-evaluate and to fully appreciate the unique conditions and species combinations available for original study in the context of Australian soils and conditions.

Identification Guides to Australian Earthworms

For fieldworkers, the difficulties of collecting and identifying specimens, due to lack of adequate identification tools, are compounded by the problems of differentiating native from exotic species and of knowing the full extent of those exotic species that are present. Identification of earthworms requires magnification, some dissection at certain stages, and a reliable guide to the proven (and potential) species. Just giving a choice between half-a-dozen species will force only those choices; while omitting potential species, such as regional cosmopolitans or those from adjacent lands, help ensure their continued omission. For instance, an "Earthworm Identifier" by Baker and Barret (1994/5) appears to be based on a guide to the British fauna by Sims and Gerard (1985) and identified only a dozen (mainly lubricid) species, or less than 2% of currently known Australian species, but still managed several critical errors while also giving the allusion persisting from 19th Century literature that the main species were "the common European earthworm". Unfortunately, there are no unified keys or guides to Australian earthworms, as there are for Australian microdriles (small, aquatic worms), i.e. Pinder and Brinkhurst (1994), or for New Zealand earthworms (Lee, 1959; Blakemore, 2005). **Figure 2** shows some family characteristics. Presently, several resources must be consulted to identify the species. In summary:

Blakemore (1994), attempted a complete eco-taxonomic guide to Australian natives and exotics that is still useful, but the taxonomy now needs upgrading.

Blakemore (2000d) described 230 natives and exotics from the island state of Tasmania and keyed them with an interactive (DELTA) computer guide.

Jamieson (2000) covered 404 Australian Megascolecinae, most in superceded combinations, yet omitted ca. 200 spp, despite a 2001 revision "Supplement".

Dyne and Jamieson (2004) reviewed native (and inadvertently several exotic) Acanthodrilidae, Octochaetidae, and (doubtfully) Exxidae, erecting some names with invalid designations that must be ignored; incidentally; this publication makes

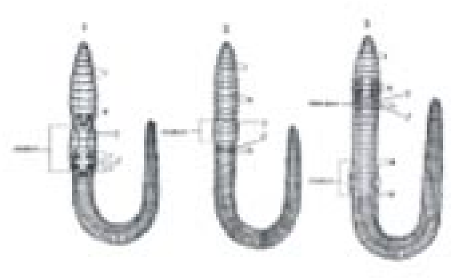

Fig. 2. Major earthworm families: 1 Acanthodrilidae, 2 Megascolecidae, 3 Lumbricidae (from Lee et al., 2000 after Lee, 1959 Tuatara VIII(1): figs. 1-3).

no reference to "ecology" for any of these species.

Blakemore (2002) presented a complete guide to taxonomy, ecology and world distributions of about 120 most common exotics, including all those known from Australia, and an update volume is in preparation.

Blakemore (2005) updated and corrected a list (publicized via ABRS, 2004) – and this new species checklist is the most complete and current tally of names.

Species Diversity and Biodiversity Results for Australia

In more urbanized or disturbed environments a few species can be collected on topsoil just digging down 20 cm. Among the commonest species the ones in Plate 1. But if the cores are made in shelterbelts and hedgerows (such as in the area of Gerangamete, Vic) some additional native species can be added (**Plate 1 a,b**).

A selection of Australian abundance and diversity studies is presented in the table below (**Table 2**) which can be compared to results from other regions. Use of faunal guides and collection methods more suitable for Europe appears to have yielded limited results in local surveys of parts of some southeastern Australian states (Baker, 2004), whereas an ambitiously titled "National Survey of the Earthworm Fauna of Urban and Agricultural Soils in Australia" based on superficial samples supplied by schoolchildren and a northern European guidebook (viz. Sims and Gerard, 1985) tried to identify specimens for which "no dissections were attempted" and yielded predictable results: just 27 mainly lumbricid taxa, or just about 4% of the currently known fauna and, of the exotics known even then (e.g. Blakemore, 1996a or b, 1997a or b), these represented just about half (Baker *et al*., 1997). This data will also under-represent deep-burrowing species.

Australia's neo-endemics are found in these (families and) genera: (Megascolecidae) *Pontodrilus* with uncertain origin, (Megascolecidae) *Begemius* from New Guinea, (Octochaetidae) *Octochaetus* from New Zealand, and (Acanthodrilidae) *Rhododrilus* and *Maoridrilus* also from New Zealand, that, if counted as exotics, would raise the total of non-natives from Australian states to about 80 species.

Although patchily sampled, high diversity has been recorded from some Australian sites – incomparable to habitats elsewhere in the world. For example, from a total of about 40 species identified during three years' observations around Brisbane in Queensland, 24 species (16 exotics + 8 natives) were located on and adjacent to a farm at Samford in south-east Queensland (Blakemore 1994; 1997a); 24 species (5 exotics and 16 natives plus 3 microdriles) were collected one week on the shores of Lake Pedder in the Tasmanian Wilderness World Heritage Area (Blakemore, 2000a); and sixteen species (10 exotics and 5 natives plus an enchytraeid) were found after a couple of weekends' surveys on a 45 ha property in the Southern Highlands of NSW (Blakemore, 2001c). While the average Australian backyard garden can support a varied community, often of about a dozen species, both known and new (e.g. Blakemore, 1997a; 2000d).

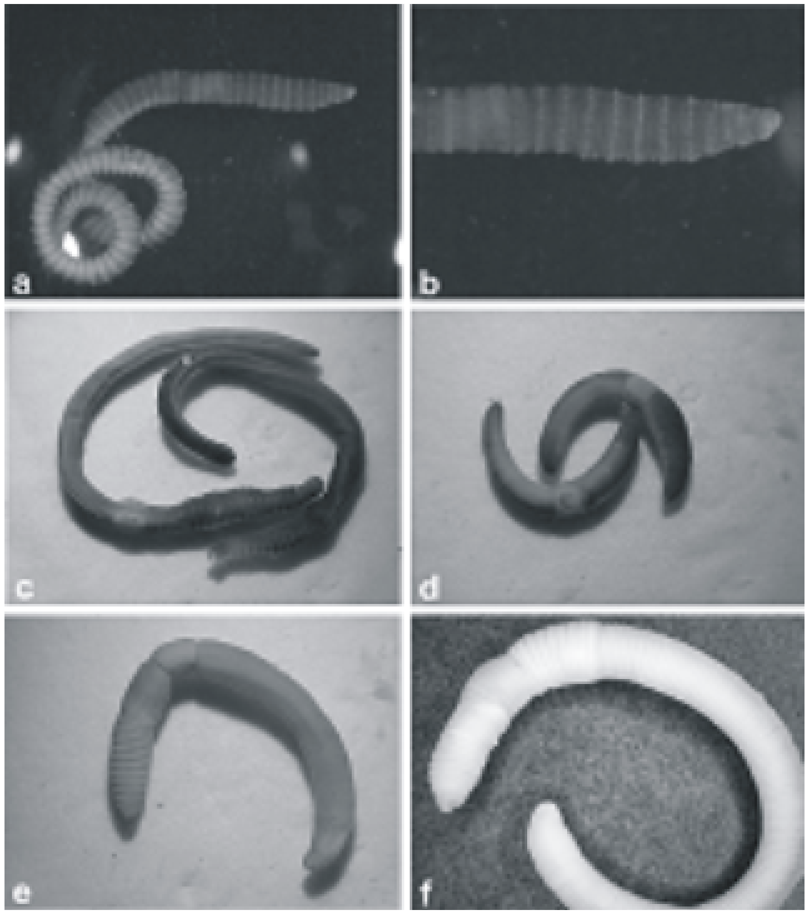

PLATE 1.Some easily found earthworms in Victoria: a,b - Native perichetine earthworm Anisochaeta macleayi (Fletcher, 1889) found in Gerangamete forest VIC. and nearby shelterbelts, c- Introduced very common species Lumbricus rubellus, d- Introduced species les common than the previous one has been found in one organic orchard in Melbourne, e- Introduced earthworm Octolasium cyaneum common in pastures, orchards with

This diversity is mainly due to persistence of natives, combined with contributions from the pool of exotics originating from various temperate and tropical regions of the world - where their origins often correspond to the eight independent centers of the world's major cultivated plants (Vavilov, 1951). These earthworms may well be attendant upon and have accompanied these crops via the spread of agriculture and world trade, although transportation of earthworms to regions they are not native to, as with the crops, is not necessarily direct. As evidence for this, the faunal lists for the Levant and Maghreb will have many names familiar to workers in other regions of the globe (see Pavlicek *et al.*, 2003; Omodeo

Table 2. Summary reports of diversity and abundance in various Australian habitats (some are totals rather than mean values) – references in Blakemore (1994; 2002)

State or Territory	Habitat	Taxa[A]	Total spp	Nos. (m^{-2})	Biomass ($g\ m^{-2}$)	Reference
SA	wheat/fallow	exotics	3	20-450	2-74	Barley (1959)
SA	Pasture	exotics	3	260-640	51-152	Barley (1959)
NSW	alpine forest	natives	10	7-135	1.2-81.8	Wood (1974)
Vict.	Woodland	natives?	N/A	25-195	N/A	Ashton, 1975
Vict.	Orchard	sexotics and natives	5?	0-2,000	N/A	Tisdall, 1978
Queesland	Rainforest	natives?	N/A	140-150	N/A	Plowman, 1979
WA	Wheatbelt	exotics	4	N/A	N/A	Abbott and Parker, 1980
Vict.	Pasture	lumbricid	5	15-21	N/A	Tisdall, 1985
WA	jarrrah forest	natives	7 + 62 spp.	4-91	0.3-27.0	Abbott, 1985a; 1985b
WA	Pasture	exotics	5	19-157	8-61	Abbott, 1985a
WA	Pasture	Native	1	N/A	30-96	Abbott et al., 1985
SA	Wheat	lumbricid	1	130-341	21-100	Rovira et al., 1987
Vict/NSW	Pasture/crops	exotics and natives	9	0-802	N/A	Mele, 1991
Queesland	Barley	lumbricid	1	9-54	0.3-5.3	Thompson, 1992
WA	Pasture	exotics	2	58-170	20-90	McCredie et al., 1992
Quessland Narayan	Pasture	natives and exotics	6	0-1,020	0-31.1	Blakemore, 1994
Quessland Samford	Arable	exotics and natives	24	0-263.8	0-68.1	Blakemore, 1994
Macquarie Isl.	Natural	exotic and neo-endemic	3	NA	NA	Blakemore, 1997
Tas. L. Pedder	Sclerophyll wilderness	Natives, exotics and translocated spp.	24	NA	NA	Blakemore, 2000b
NSW	Pasture	exotics and natives	16	NA	NA	Blakemore, 2001c
Highest	Totals	–	24	2,000	152	–

[A] exotic or introduced taxa are from various families; natives are mainly megascolecids, or in Queensland, megascolecids, octochaetids, and acanthodrilids. N/A - data not available.

et al, 2003). However, it is important to realize that native species are unique and fully adapted to Australian habitats.

Contrasting to these recent higher Australian figures, Lee (1985) and Lavelle and Spain (2001) say that earthworm communities from a wide variety of regions and habitats rarely comprise more than 8-11 species, most commonly just two to five, which Baker (2004) paraphrases as: "more commonly only two to three species are found".

The highest abundance for Australian pastures are equivalent to 6.4 million worms per ha and 1.52 t ha^{-1} (Barley, 1959) which is a biomass value higher than the usual stocking rate of a pasture. In comparison, a 1,000-year-old permanent pastures in UK stabilized with a winter population of six lumbricids at 4.6 million worms per ha and 1.53 t ha^{-1} (Blakemore, 1981; 1996; 2000c).

Earthworms in Pastures in Northern Australia

Under this heading Baker (2004: 277) states "Very little is known.." and as evidence cites Baker *et al*. (1997) documenting the exotic *Pontoscolex corethrurus*, although accepting that Blakemore (1997a or b) reported that the introductions of exotic and native earthworm species increased pasture production on brigalow soils by 64% within a year in southeastern Queensland". The number of species tested in extensive ecological experiments in the laboratory, glasshouse, and two medium-scale field trials in pastures by Blakemore (1994; 1997a) were over 30 that resulted in pasture increased of 26% and 64%. Intensive preliminary surveys revealed presence of greater than 75 species from the southeast Queensland study area.

From the whole of the Northern Territory only about 20 species are currently known (listed by Blakemore, 2005), about the same number as found in a single farm in the south (e.g. Blakemore, 1997a,b; 1999). Overviews of sustainable productivity and earthworm effects in drylands and tropics, including in the Australian region, may be found in Pearson *et al.* (1995) and Brown *et al*. (1999).

Programs to Redistribute Earthworms

Earthworms occur naturally in all soils except where recent volcanism, glaciations, inundation or desertification precludes them. Agricultural management practices that remove native vegetation with cultivation and the introduction of exotic crops or pastures, or use of toxic biocides can also deplete indigenous faunas. Thus it is only in virgin soils (e.g. post-glaciations), land reclaimed from oceans such as the Dutch polders, recently cleared lands (e.g. Brigalow in Quessland or pastures in New Zealand), or those subjected to intensive agriculture that have impoverished earthworm populations. There are many reports, from around the World, of earthworm (re-)introductions into these kinds of soils to stimulate productivity or to rehabilitate degraded soils. Unlike trials in other countries, introduction attempts in Australia have not generally been preceded with glasshouse trials (except those conducted by Blakemore, 1994), but just like other countries, use of lumbricids has yielded variable results. Findings from such trials are summarized in **Tables 3 and 4**.

Stockdill (1966; 1982) as reported by Lee (1995) documented pioneering work done in New Zealand on the effects of introduced lumbricids on the productivity of pastures which lacked them whereby

Table 3. Summary of pot experiments of earthworm effects on plant yields (references in Blakemore, 1994)

Workers	Dates	Country	Spp.	Plants	Controls (%)
Wollny	1890	Germany	lumbricids	crops	useful effects
Russel	1910	U.K.	lumbricids	?	25%
Hopp and Slater	1948	U.S.A.	lumbricids	hay/clover	48-95%
Hopp and Slater	1949	U.S.A.	*A. caliginosa/*	millet	11% NS
			Diplocardia sp.	lima beans	8% NS
				soybean tops	248%
				wheat grains	20%
Nielson	1951/3	N.Z.	lumbricids	turves and grass	31-110%
Waters	1951	N.Z.	*A. caliginosa*	rye grass	
Ponomareva	1952	U.S.S.R.	?	crops	400%?
Zrazhevskii	1958	U.S.S.R.	*A.* caliginosa	tree saplings	26% and 37%
Atlavinyte *et al.*	1968	U.S.S.R.	lumbricids	barley	92-201%
VanRhee	1965	Holland	*A.. longa/* L terrestris	grass, wheat clover	287%, 111%, 877%
Marshall	1971	U.S.A.?	*A. caliginosa/ L.terrestris*	black spruce	significant 1 yr.
Atlavynte/Pocine	1973	U.S.S.R.?	*A. caliginosa*	oats	20-50%
Aldag and Graff	1975	Germany?	*Eisenia fetida*	oat seedlings	8.7% (21% protein)
Edwards and Lofty	1978/80	U.K.	4 lumbricids	barley	increases
Graff/ Makeshin	1980	Germany	lumbricids	ryegrass	10%
Abbott and Parker	1981	Australia	*A. trapezoids*	ryegrass	-23%
Atlav./Vanagas	1982	Lithuania	*A. caliginosa*/ *L. terrestris*	barley grain	4-220%
Mackay *et al.*	1982	N.Z.	*A. caliginosa/ L. rubellus*		
				ryegrass	2-40%
McColl *et al.*	1982	N.Z.	*A. caliginosa*	ryegrass	5-50%
Atlavinyte and Zimkuviene	1985	Lithuania	*A. caliginosa*	barley	56-96%
James and Seastedt	1986	U.S.A.	*A.caliginosa*/ Diplocardia sp.	bluestems	-7-18%
Kladivko *et al.*	1986	U.S.A.	*L. rubellus*	corn seedlings	greater emergence
Sharma and Madan	1988	India	worms abd dung	wheat/maize	slight
Haimi and Einbork	1992	Finland	*A. caliginosa*	birch	200% in 119 days
Haimi *et al.*	1992	Finland	L. rubellus	birch	28.5% in 1 yr
Spain *et al.*	1992	Africa	5 tropical spp	maize	-12%-154%
			3 tropical spp	panic grass	-10%-214%
Pashanasi *et al.*	1992	Peru	P. corethrurus	tree seedlings	-80%-2,300%*
Blakemore	1994/97	Australia	28 spp.	various crops/ grasses	see reports

*Herbivory of control compromised results of Pashanasi *et al.* (1992).

Table 4. Summary of field experiment results of earthworm effects on plant yields (treatment responses expressed as a percentage of the control yields) and observations. References given in Blakemore (1994 http://bio-eco.eis.ynu.ac.jp/eng/database/earthworm/)

Workers	Dates	Countries	Spp.	Plants	Response (% ctrls)
Ribaudcourt & Combault	1907	Belgium	lumbricids	crop?	increased yields
Kahsnitz	1922	U.S.S.R	lumbricids	peas/oats	70%
Dreidax	1931	Europe?	lumbricids	winter wheat	increase
Waters	1951	N.Z.	lumbricids	pasture	correlation
Uhlen	1953	Sweden	*L. rubellus/ L. terrestris*	barley in garden	increase
Duff	1958	N.Z.	*A. caliginosa*	natural grassland	70% after 5 years
Stockdill	1959	N.Z.	*A. caliginosa*	10 yr old pasture	72%
Stockdill/ Cossens	1969	N.Z.	lumbricids	17 yr old pasture	19-45%
VanRhee	1977	Holland	*A. caliginosa/ L. rubellus*	fruit orchards	2.5%, (140% roots)
Noble *et al.*	1970	N.S.W.	A. caliginosa	pasture	10% (not sig.)
Atlavinyte	1974	USSR	*A. caliginosa*	barley	78-96%
Edwards/Lofty	1980	U.K.	4 lumbricid spp.	barley plants barley roots barley grain	57% 181% 24% (not sig.)
Atlavinyte and Vanagas	1982	Lithuania	*A. caliginosa/ L. terrestris*	barley grain rye grain	>200% + quality lower but + quality
Hoogerkamp *et al.*	1983	Holland	lumbricids	Polder pastures	10% after 10 yrs
Springett	1985	N.Z.	*A. longa*	pastures	27% after 1½ yrs
Curry & Boyle	1987	Ireland	lumbricids	reclaimed bog	25-49%
McCreadie & Parker	1991	W.A.	*A. trapezoides/ M. dubius*	wheat	62%
Temple-Smith	1991	Tas.	*A. caliginosa/ A. longa*	pasture	60-75% in 2 yrs
Blakemore	1994	Quessland	12 species	pastures	see reports

one site had a 70% increase in spring pasture production after four years, which later leveled off to about 30% higher than uninoculated fields. Water infiltration rates were doubled and soil moisture increased by 17%. Springett (1985) followed up this type of inoculation and cost benefit studies indicated that earthworm introduction presented a highly profitable development opportunity for New Zealand farmers with unpopulated pastures.

From Australia there are only a few published studies. Barley and Kleinig (1964) and Noble *et al.* (1970) both report on the introduction of *Aporrectodea caliginosa* into irrigated pastures in NSW. After 8 years there was a resultant reduction in root mat thickness, C:N ratio and bulk density of the soil. Blackwell and Blackwell (1989) working in a similar riverine clay found reasonable survival after introduction of *Aporrectodea caliginosa*, *A. longa* and

Fig. 3. (after Yeomans, 1958: Pl. 30). Keyline Outcomes: photos show the lush growth on what had been very low-grade pastures and the worms found below. "Ten centimeters of new topsoil was created in three years – something that was previously thought to take around 800 years! Earthworms emerged in abundance, the size of which (over 60 cm or 24 inches) had never been seen before in the Region". Quotes and photos from the Laceweb Homepage for Keyline system on Nevallan farm, Richmond, NSW: http://www.laceweb.org.au/ Chapter%20Three.htm Photo 16; and http://www.soilandhealth.org/ 01aglibrary/ 010126yeomansII/010126toc.html [July, 2005].

the ocnerodrilid *Eukerria saltensis* and reported increased air permeability after a year. However, *E. saltensis* has subsequently been reported as problematic in NSW rice paddies by Stevens and Warren (2000). Studies by Abbott and Parker (1981) and McCredie and Parker (1992) in WA culminated in 62% increase in wheat yield (and greatly improved soil structure) three years after introduction of *Aporrectodea trapezoides* and the acanthodrile *Microscolex dubius*. Blakemore (1994; 1997a) worked at two south-east Queensland sites that had been depleted by previous land-clearing and cultivation, introducing combinations of 12 species of native or exotic earthworms that, after one year, resulted in pasture increases of 26% and 64%, respectively, compared to control plots. These experiments were have used the most combinations of earthworm species attempted previously and the results, despite a persistent drought, were positive and encouraging (Blakemore, 1994; 1997a). These latter publications also reported attempts to relocate native earthworms, e.g. *Diplotrema capella*, *Plutellus buckerfieldi* and several other native species, but survival rates are not known due to lack of follow-up support.

Introduction of Earthworm Taxa to New Areas from Tasmania

Temple-Smith (1991) relocated two lumbricids, *Aporrectodea caliginosa* and *A. longa* in Tasmanian pastures in 1987, but no growth responses were recorded until two years later when pasture yields increased by 60-75%. A long-term adjunct to this - a project estimated to cost $500,000

(LWRRDC, 2000), aimed to introduce the deep-burrowing lumbricid, *A. longa*, from Tasmania to mainland Australia (Baker, 1997: 246; 2004: 266, 276, 277, 279). Justification for this research had three assumptions expressed thusly: First, that "the deep-burrowing *A. longa* is currently restricted within Australia to Tasmania" and "at present these worms are established in agricultural soils only in Tasmania" as it "has not yet become established on the Australian mainland" even in "high-rainfall regions of south-eastern Australia, where it does not presently occur". Second, that "deep-burrowing (anecic) species are rare, particularly in mainland Australia". And third, presumably, that merely relocating a species will ensure its survival. All these assumptions were erroneous, as much when the project started more than a decade ago, as now. It was recorded (e.g. Blakemore, 1994: 261; 1996a; 1997a:607,b; 1999; 2000d; 2002) that *A. longa* was already present nationally; e.g. from "Australia" according to Gates (1972) or "Australia (including Tasmania)" by Sims and Easton (1985; 1999), and from every Australian state, viz. NSW (Fletcher, 1886: 546; Wood, 1974; Blackwell and Blackwell, 1989); Victoria (Tisdall, 1985); WA (McCredie and Parker, 1988); Quessland (Robertson, 1989); SA (J. Buckerfield pers. com); and the ABC Landline (Aug 17, 1997 http://www.abc.net.au/landline/ll170897.htm) also reported that "farmers from Victoria have transferred thousands of these underground soil conditioners to their own properties at Mortlake". Moreover, it is probable that the specimen of *A. longa* found by Baker (2004) "by chance" approximately 20 m from a release site in a pasture in the ACT, was part of a resident population rather than a survivor, as this worm is in gardens in Canberra's suburbs (Blakemore, unpublished). There have been too few comprehensive surveys in Australia to make such broad statements about this, nor any other species' full distribution range, especially when it is deep-burrowing and thus likely to be missed by superficial survey.

Instances of deep-burrowing natives are reported, for example, Abbott *et al.* (1985) in WA tracked the native *Megascolex imparicystis* burrowing in arid sandy soils to a depth of 5 m; Blakemore (1994; 1997a or b) excavated native Acanthodrilidae species (e.g., *Diplotrema elstobi*, *D. narayensis* and *D.* sp. nov?) quiescent at up to 1 m depth in arid clay pastures in Queensland. In northern NSW farmland *Digaster biracemea* and *Heteroporodrilus doubei* occur more than 30 cm down, but are believed to feed at the surface (anecic); *Heteroporodrilus bongeen* was found at depth in the cropping soils of the Darling Downs, and in the vertisol plains of central NSW *H. mediterraneus* significantly contributes to subsoil hydration and aeration (Friend and Chan, 1995 or 2001). In the Southern Highlands, NSW, several species including the giant *Notoscolex grandis* and *Anisochaeta austrina* plus other unidentified native species were found one weekend under pasture at depths of 50-60 cm where the deep-red, basaltic soil was riddled with burrows of ca. 1 cm diameter in both horizontal and vertical planes (Blakemore, 2001a; 2002b); in total, 14 species of earthworms were unearthed at various habitats on this 45 ha property, and of these only 5 (ca. 30%) were Lumbricids.

In Victoria, *Megascolides australis*, now a protected species, is also deep burrowing to 2m in the Gippland dairy region (van Praagh, 1992), while Blakemore (2000d) reported *M. tasmanicus* "at about 1-1.5 m depth, but some burrows were also as deep as 5 m".

Contrary to earlier beliefs, several native species may also be widespread in agricultural soils, e.g. several *Anisochaeta* spp., such as *Anisochaeta macleayi*, have wide distributions extending from Queensland to Tasmania (Blakemore and Elton, 1994; Blakemore, 1999; 2000 a or b or c), *Fletcherodrilus* spp. occur from Queensland to NSW (Blakemore, 1994), *Heteroporodrilus* spp. are found through out the Murray-Darling river basin (see Blakemore, 1994; 1997a; 2000b: Fig. 20) and several natives, mainly *Diplotrema* or *Octochaetus*, were described from pastures in NSW and Queensland (e.g. Blakemore, 1994; 2001). This is just a sample of our current knowledge of ecology of the natives, whether deep-burrowing or not. Continued reliable surveys can be expected to reveal much greater habitat and species diversity, and much more ecological complexity in Australia.

Finally, the survival of any species in a particular area will depend on its precise adaptations, and it is perhaps more important to investigate not only the correct identification and full distribution, but also the ecological requirements and associations (cf. Wills and Abbott, 2003).

Nevertheless, it now seems that the publicly-funded *A. longa* mass-rearing program is abandoned as Baker (2004: 276) invites "private industry … to follow up this research". It is hoped that a responsible attitude towards identification of study material and quarantine prevails, as there is a real risk of inadvertent introduction of undesirable species to the mainland, such as the externally similar and equally deep-burrowing *Lumbricus terrestris* that has become a problem species since its introduction to North America, and that, after Blakemore (1997a/b/c; 2000a/b/c), is now known to occur sympatrically with *A. longa* in Tasmania.

Value of Introducing "New Earthworms Species" into Australia

In a summary section, Baker (1998; 2004) advocates introducing exotic species from southern France to Australia and Baker (1998; 2004) further claims that "Broad-scale surveys and intensive, seasonal monitoring of field population suggest that the current earthworm fauna in agricultural fields is represented poorly by deep-burrowing species … but it is unlikely that *A. longa* will successfully colonize the strictly Mediterranean climatic regions. For instance, the natural distribution of *A. longa* does not extend into Mediterranean regions of countries such as France." This seems to be counter indicated, not just by its occurrence already, as noted above, in every state in Australia, but also by the known distribution range of *A. longa* in the French Riviera (e.g. Csuzdi and Zicsi, 2003), as well as being widely introduced extra-tropically in North America (e.g. California), Mexico, South America, the Magreb, Asia, and in "Australia (including Tasmania)" (e.g. Gates, 1972; Sims and Gerard, 1985; 1999). Baker (1998; 2004) asks: "It is sensible to question the likely suitability of strains of [lumbricid] earthworms from such [cool temperate

European] countries when faced with the warmer and drier habitats in much of southern Australia and whether Mediterranean strains of the same or other species might be more appropriate (Baker, 1998a,b)… We actively select climatically sensible strains or varieties of agricultural plants and biocontrol agents, so why not also earthworms?”. An obvious reply is that firstly we must complete the groundwork to survey just what native and exotic species occur, and where in Australia. And, secondly, the "ecological appropriateness" of a species will be revealed by its current survival and distribution in Australian soils. Nevertheless, it seems this venture was already attempted as a CSIRO Report (http://www.ento.csiro.au/history/rr93-95/pm_ma.htm) states “A 1994 survey of earthworms in temperate and Mediterranean regions of France provided initial specimens to begin such research." At a time we face a "Taxonomic Impediment", as shown by Wills & Abbott (2003) when we know only a fraction of the biodiversity of the Australian continent and face problems of describing new material that relate to a lack of trained taxonomists, lack of incentive, and uneven distribution of funding, it seems inappropriate to advocate or publicly fund introduction of yet more potentially damaging exotics.

Inoculation of inappropriate species that will not survive in particular habitats is as futile an exercise as is the subsequent return to deleterious management practices that will disfavor their continued survival. Moreover, deliberate introduction will only fast-track recolonization by natural processes into soils where conditions suitable for maintained earthworm habitation are using beneficial practices such as mulching, covercrops, swales, stubble retention/reduced tillage, companion planting, and ley rotations, and avoiding deleterious practices, as summarized in the next section.

Effects of Management Practices on Earthworms

“The bare ridges became covered with lush pasture. Erosion in the valleys ceased. Earthworms, which had never been seen, appeared in their myriads. Soon bare loose red shale became submerged in rich black soil…. In three years he has produced four inches of friable black soil where bare weathered shale or sandstone so recently comprised the barren soil….” Hill (2002 or 2003) quoting Sir C. Stanton Hicks (1955) on Yeomans’ Keyline farming results (see Fig. 3).

It now seems that, rather than introducing extraneous species, the most practical and efficient method for increasing natural productivity of soils is by management practices that enhance or create conditions most conducive to colonization or resurgence of locally endemic or adventitious, exotic earthworms. This is eloquently stated by Lee (1995) like this: “Intelligent management of earthworm populations depends on an understanding of the diversity of earthworm communities, the nature and significance of species associations, the ecology and behaviors of the individual species, and the role of earthworms as contributors to the biological processes that are a fundamental component of soil formation and soil fertility”.

Various management practices have been identified that influence earthworm diversity and activity both positively and negatively (e.g. Rovira *et al.*, 1987; Paoletti, 1988; Haines and Uren, 1990; Buckerfield, 1992; Lee and Pankhurst, 1992). Adverse operations are cultivation, vegetation clearing/burning, monoculture, stock drenching and biocide application. Whereas earthworm populations are enhanced by practices such as: mulching, reduced-tillage, cover crops, agroforestry, irrigation, liming and other ecologically compatible farming practices. Sustainability of agroecological environments may only be fully realized when techniques are implemented that encourage biodiversity and natural processes eg. those reported by Lee (1991). From the literature (e.g. Yeomans, 1958; Lee, 1985; Mollison, 1988; Haines and Uren, 1990; Buckerfield, 1992, 1993; Blakemore, 1994: Lee, 1995: 229; Buckerfield and Webster, 1996, 1998), beneficial management practices aiming to reduce severe fluctuations in physical, chemical and biotic conditions, might include:

- Maintain high humus levels by returning organic matter to soils with cover crops, stubble retention, surface mulching, and (ley) rotations.
- Reduce erosion (e.g. contour ploughing, Keyline design, slowing water rills).
- Reduce compaction from trampling and traffic (e.g. cell grazing, wide tyres, avoiding land when waterlogged).
- Provide shade, windbreaks, and nature corridors with trees, shelterbelts, and deep fence-lines (windbreaks can reduce soil evaporation considerably).
- Reduce or eliminate tillage and promote furrow sowing.
- Reduce or eliminate toxic chemicals (biocides and drenches) in favor of IPM
- Build swales or divert channels to conserve water, or irrigate.
- Raise pH by applying lime or add gypsum to sodic soils.
- Maximize ‘edge-effects’ by increasing interface boundaries, e.g. dam/field/ forest.
- Performing cost/benefit analyses factoring in biodiversity, soil structure and water conservation assessments.

Some successful implementations examples are from Haines and Uren (1990) who found the biomass of earthworms under direct drilling was twice that of conventional cultivation, while total worm numbers increased from 123 to 275/m^2 when wheat stubble was retained compared to stubble burning. Trials using mulch in vineyards resulted in significantly higher soil moisture, higher earthworm populations and increases in grape yields of 45% within eighteen months (Buckerfield and Webster, 1996). Baxter (1997) reports less erosion and increase earthworms and soil moisture by nurturing biological processes on a WA farm. Organic practices seem to have most beneficial effects, e.g. Blakemore (1981a or b; 1996a or b; 2000) demonstrated that organic sections had enhanced earthworm diversity, and numbers increased up to 4 times, compared to plots subject to conventional agriculture (see also Buckerfield, 1993).

In this context earthworms may be linked to monitors of the health of soil systems and several workers have suggested that earthworms may be suitable as bioindicators (Rovira *et al.*, 1987; Lal and Stewart, 1992; Buckerfield *et al.*, 1997; Paoletti, 1999) and it has been suggested that farmers should aim to increase earthworm populations, rather than concentrations of soil nutrients, as noted in the following section.

Earthworms as Indicators of Sustainable Production, the Farmer's Perspective

"Even without appreciating or knowing much about the soil life he cannot see, the farmer will know that his soil is as it should be when he can see that it contains a large and vigorous population of earthworms". P.A. Yeomans (1958).

In the concluding section, Baker (2004: 278) at first states "It is important that farmers recognize the species of earthworms they have on their farms, realize the varying abilities of different species to influence soil properties and plant production, and note the strengths and weaknesses of their earthworm resource". He then laments the lack of keys to species, and suggests revising Baker and Barrett (1994), presumably increasing it from just a dozen species. Baker (2004) continues: "The fact that the earthworm fauna of Australian agricultural habitats is dominated by introduced species raises an immediate question: How far have these species spread to occupy sites that are suitable for them?" The answer, apart from the realization that exotics are often only a component of the fauna in most situations rather than most dominant, is perhaps just as far as they can be found by reliable survey and, since many of the exotics and a few natives are known to have parthenogenetic morphs, in principal just a single specimen is needed for establishment (e.g. Sims and Easton, 1999). Solutions and suggestions for improved ecological studies are given in the summary below.

Summary and Conclusions

Despite a wealth of endemic species most experiments in pots or the field have historically used lumbricids, that is members of the family Lumbricidae e.g., *Aporrectodea*, *Eisenia* and *Lumbricus*. However, several earlier reports fail to adequately differentiate between species within the *Aporrectodea caliginosa* complex *sensu* Blakemore (2002). Prior to Blakemore (1994), only about six lumbricids and about the same number of tropical species had been studied in any detail with regards their effects on plant growth (Lee, 1992). Considering that there are about 715 Australian native and exotic species, and that possibly many more remain undescribed, then the range of material available for study is enormous, and slowly we are assembling much more information (e.g. Brown *et al.*, 1999). Much work is still required to better understand the most effective combinations of species, especially natives that are adapted to particular edaphic conditions necessary for sustained plant production. Preliminary work by detailed eco-taxonomic survey and production of useful species guides is yet required, even within the most populous areas of Australia, in order to comprehend and preserve this vital resource.

Solutions to any perceived lack of abundance and diversity of species and realization of their value for biomonitoring would require:

- Relevant, accurate and referenced eco-taxonomic surveys.
- Comparisons of earthworm populations on organic and integrated farms with those on other farming systems.
- Compilation of complete, comprehensive and reliable guides to species.
- Retention of voucher specimens in public institutions (and GenBank database).
- Realization that earthworms, as with any other organism, will be constrained by the most limiting factor, eg. soil moisture, soil temperature, adequate food; and the need to modify the environment accordingly.
- Realization that adding worms to an area is unlikely to succeed unless the species have prior adaptation (natives or exotics with wide tolerances).

Realization that, as biological entities, the abundance will change with time in either a positive or a negative way, and seeder populations of some parthenogenetic (self-reproducing) morphs mean that potentially just one specimen can start a colony.

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