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Urban domestic gardens (II): experimental tests of methods for increasing biodiversity

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Abstract. The extent and continued expansion of urbanisation has focused attention on the significance for native biodiversity of those green spaces remaining within such areas and the most appropriate methods of managing them. In the UK, a high proportion of urban space is comprised of the private or domestic gardens associated with residential dwellings, and many recommendations have been made for simple changes to improve their value for biodiversity ('wildlife gardening'). Here, we report the results of replicated experimental tests of five such common recommendations, involving the introduction to gardens of (i) artificial nest sites for solitary bees and wasps; (ii) artificial nest sites for bumblebees; (iii) small ponds; (iv) dead wood for fungi and other saproxylic organisms; and (v) patches of nettles *Urtica dioica* L. for butterfly larvae. The broad conclusion is that whilst some methods for increasing the biodiversity of garden environments may be very effective, others have a low probability of success on the timescales and spatial scales likely to be acceptable to many garden owners. If one of the functions of small scale biodiversity enhancement is to develop and encourage awareness of biodiversity and its conservation, then encouragement to conduct particular activities must be balanced with a realistic appraisal of their likely success.

Introduction

Increasing attention is being paid to the role of domestic (private) gardens in maintaining biodiversity in suburban and urban areas, particularly with the continued expansion of urbanisation; a large number of Local Biodiversity Action Plans in the UK explicitly address urban green spaces (JNCC 2001). Evidence of their potential importance includes (i) the high biodiversity that can be associated with the few domestic gardens for which this has been studied in any detail (e.g., Owen 1991; Miotk 1996; Anonymous 2001), (ii) the occurrence of nationally and regionally scarce species in domestic gardens (e.g., Owen 1991; R.M. Smith et al., unpublished data), (iii) the high proportion of populations, high density or high productivity in suburban and urban gardens of some species that have experienced severe declines in the wider countryside as a consequence of agricultural intensification (e.g., Swan and Oldham 1993; Doncaster 1994; Gregory and Baillie 1998; Mason 2000; Goulson et al. 2002), and (iv) the often large summed areal extent of domestic gardens relative to that of other forms of suburban and urban green space (e.g., public parks, urban nature reserves).

In the UK, this significance of domestic gardens presents both constraints and opportunities. On the one hand, being privately owned these areas by definition typically lie outside the immediate control (and hence management requirements) of local government and other administrative authorities. Moreover, ownership of the resource is highly fragmented. For example, in Sheffield, one of the larger cities in the UK, domestic gardens cover ca. 23% of the urban land area, but this garden area is distributed amongst ca. 175,000 households. Thus, safeguarding and improving the influence of urban domestic gardens on biodiversity cannot readily be achieved through the usual statutory tools. On the other hand, huge sums are spent annually on management of domestic gardens in the UK; nationally for the period July 1999 to June 2000, the retail market for garden products was valued at £2.62 billion, with 60% of households spending money on their gardens and an average spend of £183 (about 1% of household expenditure; Horticultural Trades Association Garden Industry Monitor, unpublished). This suggests that there is tremendous potential for making these spaces more suitable for biodiversity; even the use of a small proportion of this expenditure could well make a significant difference.

In this vein, the popular media (including books, magazine articles, radio and television programmes) are replete with recommendations as to simple changes that can be made to improve the value of gardens for biodiversity (e.g., Knight 1954; Soper 1975; Baines 1985, 2000; Gibbons and Gibbons 1988; Hill 1996; Moss and Cottridge 1998; Packham 2001; Harris 2002). The origins of many of these recommendations are, however, obscure or unclear, and evidence of their effectiveness remains largely anecdotal or based solely on observational data, with the associated difficulties of distinguishing causality (e.g., Anonymous 2001; Ansell et al. 2001). Replicated experiments to evaluate the frequency with which particular management actions have an observable influence on garden biodiversity on an appropriate time scale are largely wanting. Whilst there is little likelihood of most such actions having a marked negative or otherwise undesirable impact, endorsement of their widespread application would be greatly enhanced by formal experimental support. Since the average garden owner might reasonably be expected to persevere with a management action for perhaps 1–3 years, it is particularly valuable to determine which recommendations can make a positive difference to biodiversity over this period.

In this paper, we report the results of such a set of simple experimental manipulations. This study constitutes part of the Biodiversity of Urban Gardens in Sheffield project (BUGS), a broader investigation of the resource that domestic gardens provide for biodiversity and ecosystem functioning, the factors that influence the levels of biodiversity associated with different gardens, and ways in which features of gardens can be manipulated to enhance native biodiversity (Thompson et al. 2003).

Methods

The experiments were conducted in the city of Sheffield, South Yorkshire (53°23′N, 1°28′W), which lies approximately central to England. The administrative boundaries of the city extend over a region of more than 360 km^2 (Sheffield City Council 1991). However, this includes substantial areas of the Peak National Park, and areas of farmland, of quite different character from those of the urban areas. The predominantly urbanised area, in which nearly all of the human population live, has an extent of approximately 143 km^2. The majority of experimental manipulations (see below for exceptions) were conducted in 34 gardens predominantly in the southwest part of the urbanised area of the city. This provided relative consistency of the surrounding matrix, which comprises predominantly residential areas, with mixtures of terraced, semi-detached and detached housing, numbers of mature trees, and a complex network of inter-connected green spaces chiefly comprising domestic gardens. However, close control over the surrounding matrix was not required, as the object was to determine how well different experimental manipulations performed in typical garden settings (as would be the case if the respective garden owners chose to conduct them), rather than how well they performed when all other variables were tightly controlled.

Recommendations for ‘wildlife gardening’, in the broad sense, often involve quite major alterations to the structure and floral composition and diversity of gardens, e.g., the ‘woodland edge’ concept of Baines (2000). Since we were reliant on the cooperation of private garden owners, we were limited to temporary, reversible ‘add-ons’ to existing gardens. This, of course, means it is possible that some of our manipulations might differ in their effectiveness in the context of a more concerted effort to attract wildlife.

We tested five recommended methods of improving biodiversity in domestic gardens. All were simple to conduct, and thus in principle their widespread application by garden owners should not be difficult. The five methods were the introduction to gardens of (i) artificial nest sites for solitary bees and wasps (hereafter termed solitary aculeates); (ii) artificial nest sites for bumblebees; (iii) small ponds; (iv) dead wood for fungi and other saproxylic organisms; and (v) patches of nettles *Urtica dioica* L. for butterfly larvae. Note that all five provide extra habitat or nesting sites and therefore might reasonably be expected to result in increases in breeding populations of species and not simply the movement from one garden to another of individuals already present in the urban landscape (we did not, e.g., examine the effects of providing food for garden birds, whose population effects at the scale of the individual garden are difficult to evaluate).

Two other planned manipulations, the introduction to gardens of combinations of patches of nettles *Urtica dioica* L. and buddleia *Buddleja davidii* Franch for butterfly larvae and adults, respectively, and the creation of areas of long grass for grass-feeding butterfly larvae, were discarded at an early stage. In the first case this was because a very high proportion of gardens were found already to contain buddleia, making a meaningful manipulation difficult to achieve, and in the second case garden owners were typically found to be extremely reluctant to allow, even relatively small, areas of lawn to go uncut for significant periods (often from a concern as to how their neighbours would react), and so this manipulation was abandoned entirely. This serves to underline the diversity of considerations in making recommendations for wildlife gardening.

Table 1. Specifications of artificial nests for solitary aculeates used in 20 gardens, 2000–2002.

Type of nest site	No. of holes per unit	Hole diameter (mm)	Approximate depth (mm)
Tin can	70+	4	90
	70	6	90
Wooden block	25	4	90
	16	6	80
	9	8	70
	5	10	60
Plastic pipe	50–80	4–8	180

For practical reasons, more than one experiment was conducted in each of the gardens used. However, combinations of experiments were chosen such that there seemed little likelihood of strong interactions between their effects.

Solitary aculeate nest sites

Artificial nest sites for solitary aculeates and bumblebees were based on designs recommended in popular and educational literature (e.g., Prŷs-Jones and Corbet 1991; O'Toole 1992; Munn 1998), some of which have since been used commercially (O'Toole 2000, 2002). The artificial nest sites for solitary aculeates were hung from a 1.5 m stake in sunny, south-facing locations, and three designs were used across 20 gardens (Table 1):

(i) Tin cans – Paper straws were packed in cans (105–110 mm height, 70–75 mm diameter, externally spray-painted in green). Two cans were placed in each of 20 gardens in 2000, and one can in each garden in 2001 and 2002.
(ii) Wooden blocks – Blind holes were drilled in untreated sawn 'red pine' blocks (50 mm × 50 mm in section, 100 mm length). In 2000, eight blocks, two of each hole diameter (10, 8, 6, 4 mm), were stapled together and placed in each of 20 gardens. In 2001 and 2002, two sets of four blocks were stapled together, each bearing one block of each hole diameter, as these were easier to suspend.
(iii) Plastic pipe – Sections of bamboo cane were packed in plastic drainage pipe (coloured terracotta, 110 mm diameter, cut in 200 mm lengths) and capped at one end with a 112 mm postal tube bung. Two pipe sections were used per garden in 2000, and one in 2001 and 2002.

In 2002, an additional, more extensive, study of nest site use by solitary aculeates was carried out. Two blocks containing all four hole diameters (2 mm × 10 mm, 3 mm × 8 mm, 4 mm × 6 mm, 5 mm × 4 mm) were placed in each of 80 gardens, throughout the urbanised area of Sheffield. One block was attached to a wall, fence or tree, in a sunny location, and the other in the shade, at 1–2 m above the ground, to test the effect of position. The 80 gardens included as a subset those sites already being used for other artificial nests.

All artificial nest sites for solitary aculeates were placed in gardens between 5–18 April 2000, 3–6 April 2001, and 25–28 March 2002. They were collected in the following autumn or winter: 26 and 27 September 2000, 22 and 23 January 2001 and 14–18 October 2002. The occupied nests of solitary aculeates, identifiable by entrance seals of mud, or saliva and wood fibres, were held in an unheated building until late spring, then transferred to a laboratory environment (at ambient). The new generation of adult insects, and their parasitoids, were collected during the course of the summer in emergence traps (for 2000 and 2001), of which there was one separately for the occupied nests obtained from each garden. A national expert checked the identifications of all the solitary aculeate species. The collection of occupied nests meant that none remained in gardens the following year. Therefore nest use in each season was due to fresh colonisation, rather than re-use by the offspring of the previous year.

Bumblebee nest sites

Three designs of nest site were used for bumblebees, intended to attract either predominantly below-ground (*Bombus lapidarius* L., *B. lucorum* L. and *B. terrestris* L.) or at least partially above-ground (*B. hortorum* L., *B. pascuorum* Scopoli and *B. pratorum* L.) nesting species (Prŷs-Jones and Corbet 1991):

(i) Terracotta pots – 200 mm high and 130 mm mouth diameter, and with the drainage hole sealed, these were up-turned on 165 mm × 270 mm aggregate tiles, sitting on a brick, such that the lip of the pot overhung the tile by ca. 20 mm. Pots were filled with a handful of upholsterer's cotton, and one placed in each of 20 gardens, in a sheltered location out of direct sunlight, for example at the rear of a flower border, or at the base of a hedge or shrub.

(ii) Buried terracotta pots – The same kinds of pot were employed as above, but with the drainage hole unsealed, placed on a tile only and buried just below the ground surface so that the drainage hole was the sole access to the pot. One pot was buried in each of 12 gardens, in 2001 and 2002, in a sheltered location out of direct sunlight.

(iii) Wooden boxes – an untreated plywood box was constructed according to a standard design (Prŷs-Jones and Corbet 1991; O'Toole 1992), essentially comprising an antechamber with 20 mm access hole, a ventilated main compartment, and a sloping lid to shed water, raised off the ground by wooden battens. A handful of upholsterer's cotton was placed in the main chamber as insulating nest material. The box was placed in a sheltered location out of direct sunlight. It has been suggested that nests carrying the odour of rodents are more attractive to nest-searching bumblebee queens, as under natural conditions many bumblebees preferentially use old rodent nests (Free and Butler 1959, and references therein). In 2002, we tested this hypothesis.

> Upholsterer's cotton that had been used as bedding by domestic mice for 1 week was placed in half of the upturned pots and wooden boxes, whilst the remainder received fresh material. Two boxes, one containing treated and the other fresh upholsterer's cotton, were placed in each garden. The bedding treatment was balanced between new boxes and those deployed in the previous year.

All artificial nest sites for bumblebees were placed in gardens between 5–18 April 2000, 3–6 April 2001, and 25–28 March 2002, sufficiently early for the bulk of species, although perhaps not for some early-season individuals. Bumblebee nest sites were sited in the same 20 gardens as those used for nest sites for solitary aculeates, with buried terracotta pots occurring in a subset of the 20. Occupancy was monitored during the course of each season, and final assessments of evidence of their use were made at the same times as the collection of solitary aculeate nest sites (see above).

Ponds

To test the validity and potential colonisation of small aquatic habitats for freshwater organisms, small ponds were established in the form of plastic planter troughs (length: 700 mm, width: 300 mm, depth 250 mm; volume 0.028 m^3 (28 l); area at the water surface: 0.21 m^2). For practical reasons the ponds were not sunk into the ground, but access for terrestrial animals was aided by fixing a piece of stiff plastic mesh as a ramp from the ground up and into the pond. A layer of horticultural grit sand was placed on the floor of each pond, and it was filled with tap water. It was anticipated that anyone creating a pond would probably introduce pond weed, and attendant organisms, at the outset. Therefore, four 150 mm lengths of Canadian waterweed (*Elodea canadensis* Michx.) and 300 water fleas (*Daphnia* sp.; both obtained from a commercial aquatics supplier) were introduced, the water fleas one week after filling. The pond weed was cleaned manually, and rinsed briefly in dilute ethyl alcohol, to remove as many organisms as possible (retaining macroscopic specimens for reference), so that natural colonisation might be studied. Water fleas were added as prey items for colonising carnivorous insects, and to consume algae. A combination of smothering with suspended silt, and cleaning damage, resulted in poor survival of pond weed in 2000, so a second set, only cleaned manually, was introduced in spring 2001.

The ponds were established in 19 gardens on 10 and 11 July 2000. They were located in positions that did not receive sunshine throughout the day in summer, so as to discourage algal growth, but were not covered to prevent leaves falling into them in autumn. The ponds were sampled from 8–12 August 2000 and 13–21 July 2001 to monitor the status of the pond weed and *Daphnia* populations, and to record colonising organisms. An inventory of the contents of each pond was made from 17–21 June 2002; the bulk of weed and leaf litter was first cleaned of organisms in the pond water then discarded, and the water was then poured through a

350 µm sieve. All recovered organisms were stored in 70% ethyl alcohol and later sorted and identified.

Dead wood

Piles of dead wood were placed in gardens principally to test how quickly these would be used as a resource by fungi and other saproxylic organisms. Freshly cut logs of birch (*Betula pendula* Roth) from Loxley Common, Sheffield (Ordnance Survey grid ref. SK 307907), were stacked in each of 20 gardens, six logs per garden (lengths 600–800 mm, diameters 70–150 mm), on 15 and 16 November 2000. Log piles were located out of direct sunshine, at the base of vegetation or at the rear of borders. The logs were recovered from gardens between 14 and 18 October 2002. Having first recorded any organisms observed beneath the logs, the logs themselves were sealed in polythene sacks, along with litter that had collected upon and beneath the stack. Further organisms were collected off the logs in the laboratory, and specimens were collected from the litter using Tullgren funnels. All specimens were preserved in 70% ethyl alcohol.

Nettle patches

It is frequently stated that nettles growing in gardens can act as food plants for the larvae of the following butterflies: small tortoiseshell, *Aglais urticae* L., peacock, *Inachis io* L., red admiral, *Vanessa atalanta* L. and comma *Polygonia c-album* L (e.g., Chinery 1977; Fry and Lonsdale 1991; Hill 1996; Baines 2000; Packham 2001). To test the effects of small nettle patches, nettle rhizomes were dug from a single clone and planted in 0.02 m^3 (20 l) tubs (soil surface area of 0.10 m^2), using peat-free compost (Homebase own-brand) mixed with polyacrylamide gel (for water retention, made up as per instructions, and 1000 g of horticultural grit sand per tub. One tub with young nettle growth was placed in the garden border of each of 20 gardens, sitting on the soil, on 12 and 13 June 2000 (this was rather late in this season, but the patches were maintained throughout the following two seasons). This was then monitored during the summer and autumn for the presence of caterpillars, drawing evidence from characteristic feeding damage and old larval webs, and direct observation (8–17 August and 26, 27 September 2000, 12–16 July and 12, 13 September 2001, and 12–14 August and 14–18 October 2002). To test the attractiveness of new growth, half of the nettle stems in each pot were harvested during the first visit, and all growth was harvested in the autumn.

In 2002, the effect of nettle patch size in attracting ovipositing female butterflies was tested by placing groups of four tubs in one half of the gardens, and retaining a single tub in the remainder. New tubs for 2002 were balanced with old tubs across patch size treatments (i.e., ‘single tub’ gardens had five with new and five with old tubs; ‘four-tub’ gardens comprised five with three new: 1 old, and five with four new tubs). In 2002, all tubs were placed in saucers in order to retain as much water as possible, and fertiliser granules (J. Arthur Bower's Growmore brand; NPK 7:7:7) were added to the soil surface to promote growth. In 2002 the experiment was established on 23 and 24 April.

Results

Solitary aculeate nest sites

Artificial nests for solitary aculeates were used in every one of the 20 gardens to which they were introduced over the three years of the study, being used in a total of 15 gardens in both 2000 and 2001, and in 17 in 2002. Uptake was very variable across nest designs (Table 2(a)); only bamboo sections and 4 mm holes in the wooden blocks were used in more than half of the gardens across the three years. Moreover, for each nest design, the proportion of tubes or holes used out of those available was always low (Table 2(a)). Fourteen species of solitary aculeate used the artificial nests in 2000 and 2001 (Table 3); of these, three were parasitoids (ruby-tailed wasps, Chrysididae). Two further parasitoids – a gasteruptiid wasp (1 hole, 2000) and a tachinid fly (4 holes, 2000 and 2001) – were also recorded.

Of the paired single wooden blocks introduced into 80 gardens in 2002, solitary aculeates nested in those in 36 (45%) gardens. Significantly more blocks in the sun were used (38%) compared to blocks in the shade (15%; G-test of independence with Williams' correction: $G_{\mathrm{adj}} = 10.34$, $p < 0.01$), indicating that nest site placement was important. Nest occupancy was highest in 4 mm, and then in 6 mm, holes (Table 2(b)), similar to the pattern seen in the sets of wooden blocks placed in the core 20 gardens (Table 2(a)). Of the subset of 20 gardens that contained both paired single blocks and the suite of other artificial nests, the sets of wooden blocks were occupied in 15 gardens but the single wooden blocks in only 10. Single blocks may have been less easily located due to their smaller size, or may not have been as well sited; the suites of nests were hung from a stake located in the sunniest positions in gardens, whereas the single blocks were placed where a suitable hanging position could be found (only distinguishing relatively shaded from relatively sunny locations).

Bumblebee nest sites

No bumblebee nest sites of any of the three designs employed, were used for nesting by bumblebees in any of the three years for which the experiments were conducted.

Ponds

The 19 ponds remained relatively healthy, despite their small size, during the 23 months of the experiment. Being exposed above ground level, all are likely to have

Table 2. Use of artificial nests by solitary aculeates in (a) 20 gardens in 2000–2002, and (b) 80 gardens in 2002, showing the number of gardens where a particular design was used, the range in number of holes/tubes occupied per garden for those gardens where a particular design was used, and the number of available holes/tubes per garden for each nest design.

Nest design	2000				2001				2002				All years Gardens used
	Gardens used	Per garden			Gardens used	Per garden			Gardens used	Per garden			
		Holes used	Holes avail.	%		Holes used	Holes avail.	%		Holes used	Holes avail.	%	
(a) 20 gardens in 2000–2002													
Bamboo sections	9	1–7	ca.160	1–4	3	1–3	ca.80	1–4	5	1–5	ca.80	1–6	12
Paper tube (4 mm)	2	2–5	140+	1–4	0	–	70+		0	–	70+	–	2
Paper tube (6 mm)	1	3	ca.140	2	0	–	ca.70		0	–	ca.70	–	1
Wooden block (4 mm)	8	1–11	50	2–22	10	1–6	50	2–12	13	1–10	50	2–20	17
Wooden block (6 mm)	2	2–3	32	6–9	4	1–4	32	3–13	4	1–6	32	3–19	9
Wooden block (8 mm)	0	–	18	–	2	1–2	18	6–11	0	–	18	–	2
Wooden block (10 mm)	0	–	10	–	0	–	10	–	1	3	10	30	1

Nest design	Sun	Shade	Gardens used	Per garden		
				Holes used	Holes avail.	%
(b) 80 gardens in 2002						
Wooden block (4 mm)	●		16	1–5	5	20–100
Wooden block (4 mm)		●	8	1–4	5	20–80
Wooden block (6 mm)	●		12	1–3	4	25–75
Wooden block (6 mm)		●	6	1–3	4	25–75
Wooden block (8 mm)	●		7	1–2	3	33–66
Wooden block (8 mm)		●	3	1	3	33
Wooden block (10 mm)	●		1	1	2	50
Wooden block (10 mm)		●	1	1	2	50

Table 3. Species of solitary aculeates recorded from artificial nests in 2000 and 2001. No. of gardens shows data pooled over the 2 years. For occurrence, 2000 indicates species recorded in 2000 only, 2001 in 2001 only, and 2000 + 2001 shows species that appeared in the same garden in both years (but in a single case for each species).

Species	Taxon/group	No. of gardens	Occurrence
Pseudomalus auratus Linnaeus	Ruby-tailed wasp, parasitoid	1	2000
P. violaceus Scopoli	Ruby-tailed wasp, parasitoid	4	2000 + 2001
Chrysis angustula Schenck	Ruby-tailed wasp, parasitoid	1	2000
Ancistrocerus gazella Panzer	Mason wasp	5	2000 + 2001
A. trifasciatus Müller	Mason wasp	9	2000 + 2001
Symmorphus bifasciatus Linnaeus	Mason wasp	5	2000 + 2001
Pemphredon lugubris Fabricius	Sphecid wasp	2	2000
Passaloecus gracilis Curtis	Sphecid wasp	2	2000
P. insignis Vander Linden	Sphecid wasp	2	2000 + 2001
P. monilicornis Dahlbom	Sphecid wasp	1	2000
Rhopalum clavipes Linnaeus	Sphecid wasp	3	2000 + 2001
Spilomena troglodytes Vander Linden	Sphecid wasp	2	2000
Hylaeus communis Nylander	Bee	10	2000 + 2001
Osmia rufa Linnaeus	Red mason bee	2	2000 + 2001

experienced periods of winter freezing. The re-introduced pond weed persisted, and in many cases grew vigorously, in all but two of the ponds (one of these had been disturbed by children). The introduced *Daphnia* survived in all but three of the ponds, and maintained populations of more than 1000 in 12 of them (Table 4). Significant growth of filamentous algae was recorded in all of the ponds after 1 month, and during the course of the trial proceeded to occupy more than 50% of the water surface in three cases. However, in June 2002, this was only recorded in nine ponds.

Chironomid midges and mosquitoes, which are terrestrial/aerial as adults, colonised the ponds rapidly: more than half the ponds possessed egg batches of the two groups within 10 days of establishment, and after 1 month all but two ponds had been colonised. These flies remained dominant components of the pond fauna, even though no mosquito larvae were counted in 10 ponds in June 2002 (Table 4). Few other aquatic insects with flying adults colonised the ponds; familiar pond inhabitants in the wider region, such as water boatmen (Corixidae, Notonectidae) and pond skaters (Gerridae), were never recorded. Mayflies, and the aquatic larvae of hoverflies and craneflies occurred rarely (Table 4), although mayfly nymphs were observed in one other pond on an earlier date. A hydroporous water beetle (either *Hydroporus erythrocephalus* L. or *H. incognitus* Sharp, Dytiscidae) was found in two ponds in 2000, and in one pond in 2002, represented by a single individual in each pond.

Other aquatic life recorded in the ponds was unlikely to have colonised naturally. It is assumed that the crustaceans and snails occurring in the ponds were transferred as eggs with the cleaned, but not sterilised, pond weed. Water and plants from a natural pond were introduced to one experimental pond by the garden owner, and were present for 3 days before being discovered. This pond went on to support at

Table 4. Final inventory of invertebrates made in June 2002 from experimental ponds situated in 19 gardens for 23 months. Cells show the number of gardens containing each taxon in a particular abundance class.

Taxon	Abundance				Occurrence (no. ponds)
	1–10	11–100	101–1000	>1000	
Daphnia sp.* (Cladocera: Crustacea)	1	1	2	12	16
Ostracod (Ostracoda: Crustacea)	1	0	4	10	15
Asellus aquaticus (Isopoda: Crustacea)	3	2	1	0	6
Chironomid larva (Diptera: Insecta)	0	2	12	5	19
Mosquito larva (Diptera: Insecta)	3	3	3	0	9
Cranefly larva (Diptera: Insecta)	2	0	0	0	2
Hoverfly larva (Diptera: Insecta)	1	0	0	0	1
Water beetle adult (Coleoptera: Insecta)	1	0	0	0	1
Mayfly larva (Ephemeroptera: Insecta)	2	1	0	0	3
Aquatic snails (Gastropoda)	11	1	1	0	13

*Introduced intentionally to all ponds at the start of the experiment.

least two snail species, a pea mussel (*Pisidium*/*Sphaerium*), ivy-leaved duckweed *Lemna trisulca*, and a large population of *Asellus aquaticus.* Although no amphibians bred in the two available seasons, juvenile and adult frogs (*Rana temporaria* L.) were recorded in seven ponds, despite the only access being a strip of plastic mesh.

Dead wood

After 23 months in this environment, log piles had remained undisturbed in 19 out of the 20 gardens. Decay was not visible on the birch logs placed in any of the gardens, and no saproxylic invertebrates were found to have colonised the wood. However, the logs did support four species of fungi, and a slime mould: *Hypoxylon multiforme* (14 gardens), *Coriolus versicolor* (3 gardens), *Stereum hirsutum* (1 garden), *Bjerkandera adusta* (4 gardens), and *Enteridion lycoperdon* (1 garden). Furthermore, a wide variety of organisms was recorded from the log piles (Table 5). The mean number of individuals, calculated across all organisms in a given garden, was 90 (median 74), and ranged from 18 to 273.

Nettle patches

Over the three years of the experiment, evidence was found of only two caterpillars of nettle-feeding butterflies occurring on nettle patches: two comma larvae were found on a single patch in 2000. Increasing the number of patches in 2002 made no difference to the outcome. However, the nettle patches attracted other specialist nettle herbivores, including two moth species (Table 6). Sampling across 61 other

Table 5. Occurrence and abundance of organisms recovered from stacks of six birch logs, situated in 19 gardens for 23 months.

Taxon	No. of gardens	Abundance, where present			
		Mean	Median	Min	Max
Rana temporaria (frog)	4	1.25	1	1	2
Acari (mites)	7	3.14	3	1	11
Opiliones (harvestmen)	5	1.60	1	1	3
Araneae (spiders)	15	3.40	3	1	11
Chilopoda (centipedes)	8	1.25	1	1	2
Diplopoda (millipedes)	4	1.50	1.5	1	2
Isopoda (woodlice)	19	52.8	41	1	198
Oligochaetes (earthworms)	8	8.63	2.5	1	44
Platyhelminthes (flatworms)	3	1.00	1	1	1
Mollusca (snails)	15	7.20	6	1	18
Mollusca (slugs)	16	4.81	4.5	1	10
Collembola (springtails)	16	18.9	6	1	71
Carabidae (ground beetles)	4	1.25	1	1	2
Staphylinidae (rove beetles)	1	1.00	1	1	1
Hemiptera (true bugs)	6	1.50	1.5	1	2
Diptera adults (flies)	4	1.00	1	1	1
Diptera larvae (flies)	9	2.78	2	1	10

Table 6. Insect herbivores, specialising on nettles and their close relatives (Davis 1983), recorded on experimental nettle patches from 2000 to 2002.

Identity	Order	No. gardens	Notes
Anthophila fabriciana	Lepidoptera	8	Nettle tap moth
Pleuroptya ruralis	Lepidoptera	4	Mother-of-pearl moth
Agromyza sp.	Diptera	9	Leaf-mining flies
Dasineura urticae	Diptera	2	Nettle midge, in galls
Trioza urticae	Hemiptera	7	Plant louse, Psyllidae
Liocoris tripustulatus	Hemiptera	1	Common nettle capsid bug

gardens by Malaise traps and aerial pitfall traps, and inspection of indigenous nettle patches in gardens, revealed the presence of three other monophagous herbivores that were not recorded on the experimental nettles (*Heterogaster urticae, Eupteryx urticae*, and *Macropsis scutellata*). Nevertheless, the nettles also provided a resource for invertebrate species that are not restricted to nettles: 10 true bugs (Hemiptera, of which four were predators) and 11 spiders and harvestmen (Araneae and Opiliones).

Discussion

The results of the experiments differed widely in the support that they provided for the usefulness of the different methods of increasing the biodiversity of urban domestic gardens. Some of the manipulations failed entirely, or almost so, in terms of their original objectives, whilst others were very successful.

Solitary aculeate nest sites

The introduction of nesting sites for solitary aculeates has been found to be effective in other environments (e.g., Krombein 1967; Tscharntke et al. 1998; Kruess and Tscharntke 2002; Steffan- Dewenter 2002), and indeed the group of species that exploit them, and their natural enemies, have been advocated as promising bioindicators for ecological change or habitat quality (Tscharntke et al. 1998). In the garden environment such nesting sites proved also to be highly effective, with rapid and widespread occupancy taking place.

Some species using the nest sites in this study, and their parasitoids, are of direct conservation interest. Thus, the ruby-tailed wasp *Pseudomalus violaceus*, was the second record in Yorkshire, but it is not a rare insect; it is likely to be expanding its range. Other species (e.g., red mason bee *Osmia rufa*) are being promoted as valuable pollinators in the garden environment (O'Toole 2000).

Bumblebee nest sites

Species of bumblebees occur widely across urban gardens in Sheffield: a programme of Malaise trapping in 16 gardens distributed across the city recorded nine species, with five out of seven non-cuckoo species being recorded in each of 14 gardens (R.M. Smith et al., unpublished data). Their failure to utilise the artificial nest sites provided thus seems unlikely to result simply from bumblebees not occurring in the study gardens. There are several other possible explanations.

First, bumblebees in urban environments may simply not be nest site limited. Given that they may forage over extremely large areas (for references, see Goulson et al. 2002), this is not unlikely. Doubtless, bumblebees do not nest in the majority of the gardens in which they are recorded; over 11 years, Owen (1991) regularly recorded eight (non-cuckoo) bumblebee species in her conventionally managed garden, but none ever nested there. But, garden environments in the UK have been found to provide a greater density and diversity of floral resources than farmland, and probably support larger populations of *Bombus terrestris*, at least (Goulson et al. 2002).

Second, the nest sites provided may be unsuitable. This seems particularly likely to be the case for the buried, upturned pots, which often became quite wet, suggesting that the design may be suitable only in particularly well draining soils. Placing the wooden boxes in dry but shaded conditions, and raising them on battens, nonetheless meant that these occasionally also became damp, but this seems unlikely to have played a major role in the failure of this method. Snails, slugs, woodlice and spiders colonised many of the boxes each season, but what effect this may have had is unclear.

Use by bumblebees of artificial nest boxes in agricultural situations is generally very poor (Norgaard Holm 1966; Richards 1973, 1978; MacFarlane et al. 1983; Fussell and Corbet 1992). Even though there is good evidence that bumblebees very often nest in abandoned rodent burrows (Svensson and Lundberg 1977), addition of used mouse bedding did not improve the performance of our boxes. Fye and Medler (1954 cited in Free and Butler 1959) reported 46% occupancy of wooden boxes which had been nested in by mice the previous year, although the circumstances were not directly comparable.

Third, despite following existing recommendations, the nest sites may have been placed in inappropriate places for them to be occupied by bumblebees. Previous work indicates that artificial nests are best placed where searching queens are most frequently observed, that is, sites pre-selected for suitability (Free and Butler 1959; K. Henry, personal communication). This implies that for artificial boxes to be successful, a garden must already possess features attractive to searching bumblebee queens. In the wider countryside, such features are typically undisturbed or uncultivated ground, banks, hedges, and rough grass (Free and Butler 1959), although Prŷs-Jones and Corbet (1991) report a wide variety of human-made sites. Preferences of queens searching for nest sites appears to be a good guide to the locations of the nests themselves (Kells and Goulson 2003); it is therefore possible that queens would not even search in gardens lacking certain key features. For subterranean-nesting species, banks are the most important search cue (Kells and Goulson 2003). Recent experience with a small number of boxes shows that bumblebees will colonise wooden nest boxes in gardens if they are located on banks where queens commonly search for nest sites (unpublished data). Overall, these results suggest that the key to successful encouragement of bumblebee nesting may be location and microhabitat within the garden, rather than nest design alone.

Ponds

The construction of ponds has been argued greatly to increase the species richness of urban areas, even when the extent of water involved is small (Moore 1990). The ponds experiment demonstrated that, even with a very small water body, an aquatic habitat could be maintained for nearly 3 years. Such a habitat supported a range of invertebrates, and also attracted frogs, but was not colonised by many common aquatic insects. Since most garden ponds are likely to be five or ten times the surface area as the trial ponds – a sample of 37 Sheffield garden ponds had a mean surface area of $2.53\,\text{m}^2$ (± 1.96 S.D.) – they might be expected to be more successful in attracting potential colonists (e.g., damselflies and aquatic bugs). Even if they are not used for breeding, small water bodies in gardens may enable amphibians to escape desiccation stress in summer, and so use gardens that might otherwise be inhospitable.

Provision of ponds in gardens is potentially particularly significant given the marked (though apparently decreasing) declines in their numbers in the wider countryside in the UK (Boothby et al. 1995; Haines-Young et al. 2000). In the case of amphibians, common frogs, and smooth and palmate newts have been found to occur as frequently in garden ponds as in the countryside (Swan and Oldham 1993), whereas toads and great crested newts did not. Garden ponds are frequently stocked with fish, yet common frogs and smooth newts were found to be just as likely to occur in garden ponds with fish as without (although the sustainability of amphibian populations without restocking is not known) (Swan and Oldham 1993). However, due to their small size and their relative uniformity, urban ponds are unlikely to replace the variety of ponds, and thus their resident wildlife, which have been lost in the wider countryside. Furthermore, the popularity of ponds for wildlife gardening poses potential dangers via the increased transfer of diseases or alien organisms, particularly that from garden to natural ponds (J. Foster, personal communication).

From the perspective of habitat creation in gardens of limited size, however, the two points that emerge from our results are: on the one hand, the viability of even a small, neglected container habitat as a freshwater habitat – as evidenced by the persistence of those organisms that were introduced or colonised – and on the other, the importance of introductions over dependence on natural colonisation in such habitats. In practice, we suggest that for many invertebrates transfer of material (weed, frog spawn, etc) between ponds provides the necessary colonising mechanism.

Dead wood

Faced with the prospect of placing piles of dead wood in their gardens, most garden owners are likely to do so using material derived from within the garden, from pruning or felling trees. Thus, as in the experiment reported here, on establishment of the piles the material is likely to be freshly cut. The relatively slow decay rates are likely, as was found, to limit the suitability of this resource for fungi and saproxylic organisms on the scale of a few years. Such manipulations are thus unlikely to see returns on the kinds of time scales on which garden owners tend to be interested.

Nonetheless, piles of dead wood trap litter and organic debris, and maintain a humid microclimate, that may be suitable for many groups of organisms (Table 5), providing a habitat that, without active management, would probably otherwise be absent from gardens. The tendency for municipal green spaces to be ‘tidied up’ means that this habitat is also much reduced in the wider urban environment.

Nettle patches

The failure of butterfly caterpillars to use the nettle patches placed in gardens over three years mirrors Owen’s (1991) observation that three nettle patches in her suburban garden remained unused for 15 years, even though adult butterflies were abundant; the four nettle-feeding species are well known to range widely, and frequently visit urban gardens (Owen 1991; Vickery 1995). There seem likely to be two principal explanations for this outcome. First, breeding sites for nettle-feeding butterflies may not be a limiting resource. Certainly, nettles occur widely across Sheffield, although the majority do so outside the garden environment. A recent survey suggests that *Urtica dioica* may be Britain's commonest wild plant (Plantlife 2001).

Second, whilst the patches of nettles were larger than many garden owners found acceptable (many other owners would not countenance the presence of nettle patches within their gardens), they were still small, and patch size is known to influence the use of nettle patches by butterflies and other invertebrates (Vickery 1992; Zabel and Tscharntke 1998). Even the few larger patches indigenous to the 61 survey gardens were never seen to support butterfly caterpillars. Of the four nettle-feeding butterflies, the red admiral and comma were perhaps most likely to have used the patches provided. They lay eggs singly on the host plant, and small patches should have provided a sufficient resource; the comma also selects nettles in shaded locations, so it is probably the best suited to a garden environment. In contrast, the small tortoiseshell and peacock have communal larvae, which require larger nettle patches in warm locations (Thomas and Lewington 1991; Asher et al. 2001).

Whatever the reason, the provision of nettle patches undoubtedly served to increase local biodiversity of gardens in other ways. Foremost, they encouraged the occurrence of other nettle-feeding invertebrates, including some, but not all, of the nettle specialists recorded in the urban area. Because they are so common, there is no reason to expect that nettles in gardens are important for *any* invertebrates. However, the species richness of insect predators on natural nettle patches is sensitive to isolation, with declines occurring in patches separated by as little as 25 m (Zabel and Tscharntke 1998). If nettle patches are to serve as reservoirs of natural enemies, and so support biological control (Perrin 1975), then clumps in gardens potentially provide stepping stones for predators. Indeed, patches could aid populations of all nettle inhabitants in urban areas if they reduce isolation. Whilst nettle herbivores are more sensitive to patch area than isolation (Zabel and Tscharntke 1998), only 50% of the local nettle fauna was found to have colonised 9 m^2 patches within 3 years, when they were isolated by 800 m from a large nettle patch (Davis 1975).

Controls, statistics and standards of proof

Working in private gardens placed severe constraints on our experimental methods. Experimental manipulations had to be temporary and reversible, and levels of replication were inevitably limited by the logistics of gaining regular access to large numbers of spaces owned by different individuals and with diverse arrangements for entry.

The nature of the experiments themselves also largely precluded conventional controls. First, the objective in conducting them was to determine whether the manipulations themselves were utilised by the organisms they were intended to benefit (or indeed others), rather than how they contributed to overall population levels *per se*, although in most cases there seems little doubt that if they were utilised there would be a wider benefit. Second, the destructive sampling efforts required to monitor populations of many of the target species independently of their occurrence in the experiments themselves (i.e., to see if their abundance increased in a target garden, compared with that in equivalently monitored control gardens without the experiment) would almost certainly influence the uptake of the experimental manipulations. And, of course, the actual uptake of an experimental treatment (e.g., bee nests) cannot be measured in a control garden, which by definition does not have the treatment.

We conducted few statistical tests. Partly this is because there was often no rationale for such tests: on the one hand, it seems fair to assume aquatic organisms were absent from gardens without ponds, and on the other that spiders, woodlice and molluscs were abundant in gardens with and without log piles. In many cases, also the results of our manipulations were clear-cut: out of >100 nest box x year combinations, using three different nest designs, none were used by bumblebees, while nettles in 20 gardens over 3 years were used just once by the larvae of nettle-feeding Nymphalid butterflies. Use of inferential statistics in these situations is of no value in the interpretation of the outcome. Manipulations that can be recommended to amateur gardeners must have a reasonable chance of success. Although we have no detailed idea of what ‘reasonable’ might be in this context, it is clear that nettle patches and bumblebee nests fell well below any likely threshold. Nests for solitary aculeates, however, were used in half or more of our gardens, clearly justifying their commercial promotion (O’Toole 2000, 2002).

Conclusions

The broad conclusion from this study is that whilst some methods for increasing the biodiversity of garden environments may be very effective, others have a low probability of success on the timescales and spatial scales likely to be acceptable to many garden owners. This is not to suggest that particular techniques cannot be successful (i.e., the method may in principle be sound), but that the evidence indicates the success rates at least in the short to medium term may in some cases be very low, which in turn implies a small net effect on biodiversity. Importantly, because such manipulations are intended to be carried out by individual garden owners, and necessarily in small numbers, failure of one recommended technique may serve as a discouragement to continue, or to try others. If one of the functions of small scale biodiversity enhancement is to develop and encourage awareness of biodiversity and its conservation, then we must balance the encouragement to particular activities with a realistic appraisal of their likely success.

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