Vegetative Regeneration and Distribution of *Fallopia japonica* and *Fallopia* x *bohemica*: Implications for Control and Management

by

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ABSTRACT

Fallopia japonica (Houtt.) Ronse Decraene (Japanese knotweed), an introduced, invasive, rhizomatous perennial plant, has become an increasing problem for nature conservation and land management in both rural and urban areas in the British Isles. In the native range of the plant, Japan, Taiwan and northern China, a number of varieties are recorded. Three congeners of *F. japonica* are present in the British Isles, *F. sachalinensis*, *F. japonica* var. *compacta* and *F. baldschuanica* in addition to a hybrid *F.* x *bohemica*. An investigation by postal survey of the distribution of the hybrid *F.* x *bohemica* has identified 131 records for the British Isles. Both male and female plants of *F.* x *bohemica* have been recorded. Current understanding suggests that only female plants of *F. japonica* are present in the British Isles, inferring that the only means of reproduction is through vegetative regeneration. High rates of regeneration were recorded in this study for stem and rhizome material for both *F. japonica* and *F.* x *bohemica* in an aquatic and terrestrial environment. Implications of vegetative regeneration are discussed in terms of current management practices and future methods of control. A combination of digging with a mechanical excavator followed by spraying with the herbicide glyphosate decreased the time required to achieve an effective level of control of *F. japonica* compared to spraying alone. Fragmentation of the rhizome system through digging resulted in an increase in stem density allowing a more effective delivery of herbicide. Implications in terms of costs for *F. japonica* treatment on sites awaiting re-development are discussed. Analysis of data collated from surveys of *F. japonica* in Swansea using a Geographical Information System suggest that the primary habitats infested are waste ground and stream and river banks. Results suggest that disturbance, both by natural means and by human intervention has been the primary cause of spread of *F. japonica* in the British Isles. Management strategies are proposed which take account of these results and measures are put forward to help prevent future infestations.

Keywords: *Fallopia japonica*; *Fallopia* x *bohemica*; Geographical Information Systems; Hybridisation; Japanese knotweed; Plant distribution; Plant invasions; Plant management; Vegetative regeneration; Weeds

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1.0 INTRODUCTION

1.1 BACKGROUND

"One of the primary reasons for the spread and establishment of species has been quite simply the movement around the world by man of plants, especially those brought for crops or garden ornament or forestry"
(Elton, 1958)

Since Charles Elton wrote these words in his treatise on ecological invasions 40 years ago, the effect of human induced biological invasions has become a major issue in ecology. The World Resources Institute (1998) claims that "invasions of natural ecosystems by non-native species now rank second to habitat loss as the major threat to biodiversity." Of the 4,500 established exotic pest species in the United States, roughly one fifth cause serious economic or ecological harm (World Resources Institute, 1998). Article 8(h) of the Convention on Biological Diversity adopted at the United Nations environmental summit in Rio de Janeiro in 1992 recognised this threat. Participating nations are faced with an enormous task to implement the treaty which calls for "participating nations (to) prevent the introduction of, (to) control, or (to) eradicate those alien species which threaten ecosystems, habitats or species" (Williamson, 1998).

As Elton's (1958) statement clearly indicates, human activity has dramatically increased the rate of introduction of species to new geographic regions. This study explores the introduction, establishment and subsequent invasion of *Fallopia japonica* in the British Isles in relation to its management and control. The species and its congeners, *F. sachalinensis* and *F. japonica* var. *compacta* were introduced to the British Isles as ornamental garden plants in the mid nineteenth century from their native range in Japan, Taiwan and northern China. Since its introduction, *Fallopia japonica* in particular has become a serious problem as an invasive alien species in a variety of habitats throughout the British Isles (Cooke, 1988; Beerling, 1990a; Beerling *et al.*, 1994).

1.1.1 Terminology

It is important that the attitude of scientists to introduced horticultural plants which subsequently become established outside the garden environment does not become xenophobic (Barker, 1996). Terminology is therefore required to adequately explain a situation without conferring value judgements (Eser, 1998). Rejmánek (1995) described three concepts of 'weeds', 'invaders' and 'colonisers'. From an anthropocentric viewpoint, 'weeds' can be conceptualised as plants growing where they are not desired; from an ecological perspective, 'colonisers' are plants which appear in early successional series and in a biogeographical sense, 'invaders' are plants which spread into areas where they are not native. Bazzaz (1986) and Rejmánek (1989) took the concept further and suggested that 'colonisers' are successful 'invaders' in disturbed environments. In a study of the British Flora where, of 2,990 species of plant, 1,737 (58%) are naturalised aliens (Stace, 1991), Williamson (1993) surmised that 11% of 'weeds' could be classified as 'invaders' and 47% of 'invaders' could be classified as 'colonisers'. It is against this background tha: the terminology of introduced or alien invasive plants needs to be defined.

For the purposes of this study, the terminology described by Pysek (1995) is used to describe four basic situations with regard to a plant's status and the dynamics of its behaviour:

- *Native* (indigenous) a species which evolved in the area or which arrived there by one means or another before the beginning of the Neolithic period or which arrived there since that time by a method entirely independent of human activity (Webb, 1985)
- *Alien* (introduced, exotic, adventive) a species which reached the area as a consequence of the activities of Neolithic or post-Neolithic man or his domestic animals (Webb, 1985)
- *Invasive* (naturalised) an alien species the distribution and/or abundance of which in the wild is in the process of increasing regardless of habitat (Prach and Wade, 1992; Binggeli, 1994)
- *Expanding* the range extension and/or increase in abundance of a species native to a region (Prach and Wade, 1992)

According to th s terminology, *F. japonica* in the British Isles can be described as an alien invasive species.

1.2 SPECIES INTRODUCTIONS

The introduction of new species to particular geographic ranges falls into two categories, those which are introduced intentionally for agricultural or horticultural purposes and those which are introduced accidentally as contaminant seeds in crops, foodstuffs and on imported materials such as timber and ballast. This has resulted in increasing numbers of non-native species associated with crop seed, feed and horticultural products arriving accidentally to new geographic regions. The number of species reaching new geographic areas has increased dramatically since the beginning of the last century with improved methods of air, sea and land transportation (Elton, 1958; Drake *et al.*, 1989). In Japan, the number of naturalised plants in 1867 was 20; by 1956 this number had risen to 300 and by 1997 had reached 1,000 (Enomoto, 1997). In the British Isles, introductions now account for 58% of the flora (Stace, 1991); these include *F. japonica* and its congeners which were introduced to the British Isles from Japan as ornamental plants in the middle of the last century.

1.2.1 Importation of Japanese plants to Europe

Historically, intentional introductions have relied heavily on the role of the European botanic gardens, founded from the sixteenth century onwards, to propagate exotic ornamental plants, crops and medicinal plants (Heywood, 1989). During the nineteenth century, after Japan opened for trade to the outside world, European botanists were fascinated by the wealth and variety of the Japanese flora. A constant stream of plant material was collected in Japan and sent to botanic gardens including those in The Netherlands, Belgium and England. The primary instigator of these collections between the dates of 1829 and 1844 was Philipp Franz Balthazar Von Siebold (Mac Lean, 1978). Von Siebold had been posted to Java as Surgeon-Major with the Netherlands East Indies and in 1823 was invited to accompany the Opperhoofd (Head of the Factory on Deshima) on the Netherlands trade mission in Japan at Deshima, Nagasaki. Von Siebold exercised his medical practice there and specialised in botany, taking botanical specimens as payment for his services from the local people. He visited Yedo in 1826 and was presented to the Shogun but shortly afterwards was interned at Deshima for receiving duplicate maps. Thereafter he was banished from Japan, only being allowed to return to Japan in 1859 where he remained until 1862. Between 1829 and 1844, over 3,000 copies of Japanese plants had been collected and sent to Europe. A number of European botanical collectors were sent out to Japan by Von Siebold who by this time had opened a nursery garden in Leiden and formed the Royal Netherlands Society for the Encouragement of Horticulture. Von Siebold intended that the Society should be dedicated to the acquisition of Japanese flora for "the general (scientific) benefit" rather than for the "exposition of splendour". In other words, he was intending to promote the nursery garden for scientific and botanical use rather than purely for aesthetics. In 1851 and 1852 further consignments of plants were sent back to Europe but the consignments of 1855 and 1856 were spoilt. Many more plants were collected than survived the journey with only an estimated one in seven plants arriving alive. The fact that any plants survived the poor conditions of boat travel from Japan to Europe is testament to Von Siebold's unfailing efforts in collection. Seven hundred and thirty three species and approximately 400 seeds had been collected in Japan and been sent to The Netherlands between 1829 and 1844 of which 231 plant varieties remained alive. From the seeds, 13 plant species were cultivated. By 1844, 204 plant varieties were still alive and Von Siebold was selling copies of these plants from his nursery at a cost of 60 florins (Dutch guilders) per plant. One of these plants was *Fallopia japonica.*

1.2.2 History of introduction of *Fallopia japonica* to the British Isles

F. japonica, named by Von Siebold as *Polygonum cuspidatum* was one of the many plants collected from Japan and was being sold from his nursery garden in Leiden in 1848 in groups of 'one mother plant and 25 strong plants' for 500 (Belgian) francs (Bailey, 1994). Hooker (1880a) recollected that the plant had been cultivated at Kew for a quarter of a century, originally sent from Holland. However, Lindley and Paxton (1850-51) gave a description of the plant and commented that it was "introduced by the Horticultural Society about the year 1825". The description continued "it was introduced from Japan by M. Von Siebold...it is only found to be present in M. Von Siebold's garden at Leyden" (*sic*). The Cottage Gardener (Anon, 1851) described *Polygonum cuspidatum* as being " now announced in Belgium as one of Dr Siebold's novelties, it has been cultivated for some years in the gardens of the London Horticultural Society". There is no doubt therefore that the plant originated in Japan and was imported to Europe by Von Siebold. The date of introduction however is uncertain and ranges between 1825 and 1855. Although an early date is possible, as Von Siebold was collecting plants in Japan as early as 1823, Beerling *et al.* (1994) gave the date of introduction as 1848. The plant was soon available for planting in gardens and was hailed in the horticultural journals of the time for its attractive foliage, late flowering and dramatic habit. The Cottage Gardener of 1851 suggested that it could be useful for fixing loose sand by means of its running roots (Anon, 1851). The Garden (Anon, 1879) described it as "one of the finest herbaceous plants in cultivation" and suggested it as a plant for the wild garden. However, by 1904 its invasive nature had been recognised and the Journal of the Royal Horticultural Society was advising that it "cannot be recommended for shrubberies unless most carefully kept in check" (Anon, 1904). The two congeners of *F. japonica*, the smaller and more compact *Fallopia japonica* var. *compacta* and the considerably taller and more dramatic *Fallopia sachalinensis* were also introduced to the British Isles at this time (Hooker, 1880b; 1881), the former from Japan and the latter from Sakhalin Island, north of Japan.

1.3 *FALLOPIA JAPONICA*

1.3.1 *Fallopia japonica* in the British Isles

Fallopia japonica (Houtt) Ronse Decraene is a member of the dock family (Polygonaceae) and is native to Japan, Taiwan and Northern China. The plant has many synonyms including *Reynoutria japonica* (Houtt.), *Polygonum cuspidatum* (Sieb. and Zucc.) and *Polygonum sieboldii* (De Vriese). *Polygonum* derives from the Greek *poly* (many) and *gony* (a knee) referring to the jointed stems (Coombes, 1985). Known common names are Japanese knotweed, Japanese bamboo and fleece flower (Locandro, 1973), Mexican bamboo (Figueroa, 1989), donkey rhubarb (Hawke and Williamson, 1995), Sally's rhubarb and Hancock's curse (Ellis, 1989). In Japan it is commonly known as *itadori* (Makino, 1901) which means strong plant or *sukanpo* (Adachi, pers. comm.).

F. japonica is a tall, rhizomatous perennial plant reaching a height in excess of 2 m. Stems are jointed with distinct nodes like bamboo and arise erect from extensive, strong, woody rhizomes to form dense clumps or crowns. Leaves are broad and flattened at the base and are arranged alternately on flexous branches. Small, creamy-white flowers are produced in late autumn, hanging in clusters from axillary panicles (Figure 1.1). In winter, following senescence, tall woody stems persist creating dense impenetrable thickets (Figure 1.2). For a full description of the plant see Beerling *et al.* (1994). *F. japonica* shoots appear early in the spring and grow rapidly. Young shoots are susceptible to frost and drought but the plants are able to tolerate a wide range of soil conditions from colliery spoil through alluvial soils, clays and loams to shingles and free draining mineral soils and peats (Beerling *et al.* 1994). A wide range of tolerance to pollutants is recorded with soil pH from pH 4.2 - 8.5

Figure 1.1 *Fallopia japonica* in late summer showing distinctive leaf shape and arrangement of flowers

Figure 1.2 *Fallopia japonica* in winter showing erect, woody, persistent stems

recorded by Richards, Moorehead and Laing Ltd. (1990) from 17 sites in Wales. The plant grows successfully in soils with high concentrations of heavy metals, e.g. copper (Kubota *et al.* 1988) and is resistant to high concentrations of atmospheric sulphur dioxide (Natori and Totsuka, 1984; 1988). The rhizomes and stems of *F. japonica* contain a range of chemicals which are used for medicinal purposes in Japan and China, including the treatment of schistosomiasis and various fungal infections (Anantaphruti *et al.*, 1982).

In the British Isles *F. japonica* relies on vegetative reproduction for dispersal owing to the absence of male-fertile *F. japonica* plants (Conolly, 1977; Beerling, 1990; Brock and Wade, 1992; Brock *et al.*, 1995). However, *F. japonica* is reported to hybridise with its congeners *F. sachalinensis* and *F. japonica* var. *compacta* and seeds are frequently observed on *F. japonica* plants. Although these seeds are viable under laboratory conditions, seedling establishment in the wild has not been observed (Beerling *et al.*, 1994; Bailey, 1994).

According to the classification of Grime *et al.* (1988), *F. japonica* is a competitor (C-strategist) and is listed as the most invasive alien species in Britain (Crawley, 1987). The plant has a rapid growth rate (Figure 1.3), forming a dense canopy, under which

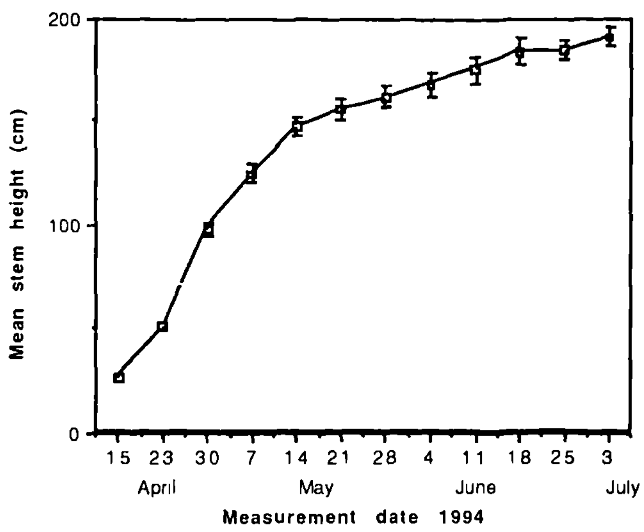


Figure 1.3 Growth rate of *F. japonica* plants at Snells Nook Lane, Nanpantan, near Loughborough during the spring and summer of 1994. Values shown are mean stem height ± 1 SE (n = 64)

few plant species can survive (Gilbert, 1989). *F. japonica* flourishes in open sunny positions; in shaded areas the stands are less dense and the plants are shorter (Beerling, 1991b).

Many environmental agencies are experiencing problems associated with the growth of *F. japonica*. In riparian situations the rhizomes may cause damage to flood defence structures (Beerling, 1991a), the dead stems cause problems with flooding, particularly in winter, and the dense growth restricts access along stream and river banks for anglers, amenity use and bank inspection (Beerling, 1990a; 1991b). The plant grows prolifically on waste ground and industrial sites, damaging structures such as car park and footpath surfaces with shoots penetrating asphalt and concrete (Welsh Development Agency, 1998b). In amenity areas the dense growth, and particularly the accumulation of dead stems from previous years growth, are aesthetically displeasing. In nature reserves and areas of natural vegetation, the dense growth of the plant outshades native vegetation, reducing biological diversity (Cooke, 1988). The seriousness with which *F. japonica* is regarded in the British Isles is demonstrated by its inclusion in the Wildlife and Countryside Act (HMSO, 1981) Part II, Schedule 9. Section 14 of the Act states "if any person plants or otherwise causes to grow in the wild any plant which is included in Part II of Schedule 9 he shall be guilty of an offence".

1.3.2 *Fallopia japonica* in Japan

The comparison of the ecology of a species in its native and introduced ranges can be very informative in explaining its invasive qualities in its new geographic region (Sukopp and Sukopp 1988). Noble (1989) and Roy *et al.* (1991) discussed the considerable interchange of species between countries at the beginning of this century. They considered that the successful invasion of a species depends more on the interaction between its biological properties and the properties of the recipient region than on the probability of reaching that region. Roy *et al.* (1991) considered that the same biological traits that enable species to spread across their native continents (and across climatic zones) also enable them to invade new continents. *Fallopia japonica* possesses a number of biological traits which enables it to survive as a primary coloniser in its native range. The distribution of the plant in its native range is shown in Figure 1.4.

Polygonum cuspidatum Sieb. et Zucc. — Perennial herb — Distr. Korea, Taiwan, China

Reynoutria japonica Houtt.
P. confertum Hook. f.
P. zuccarinii Small

イタドリ
Itadori

Polygonaceae
タデ科

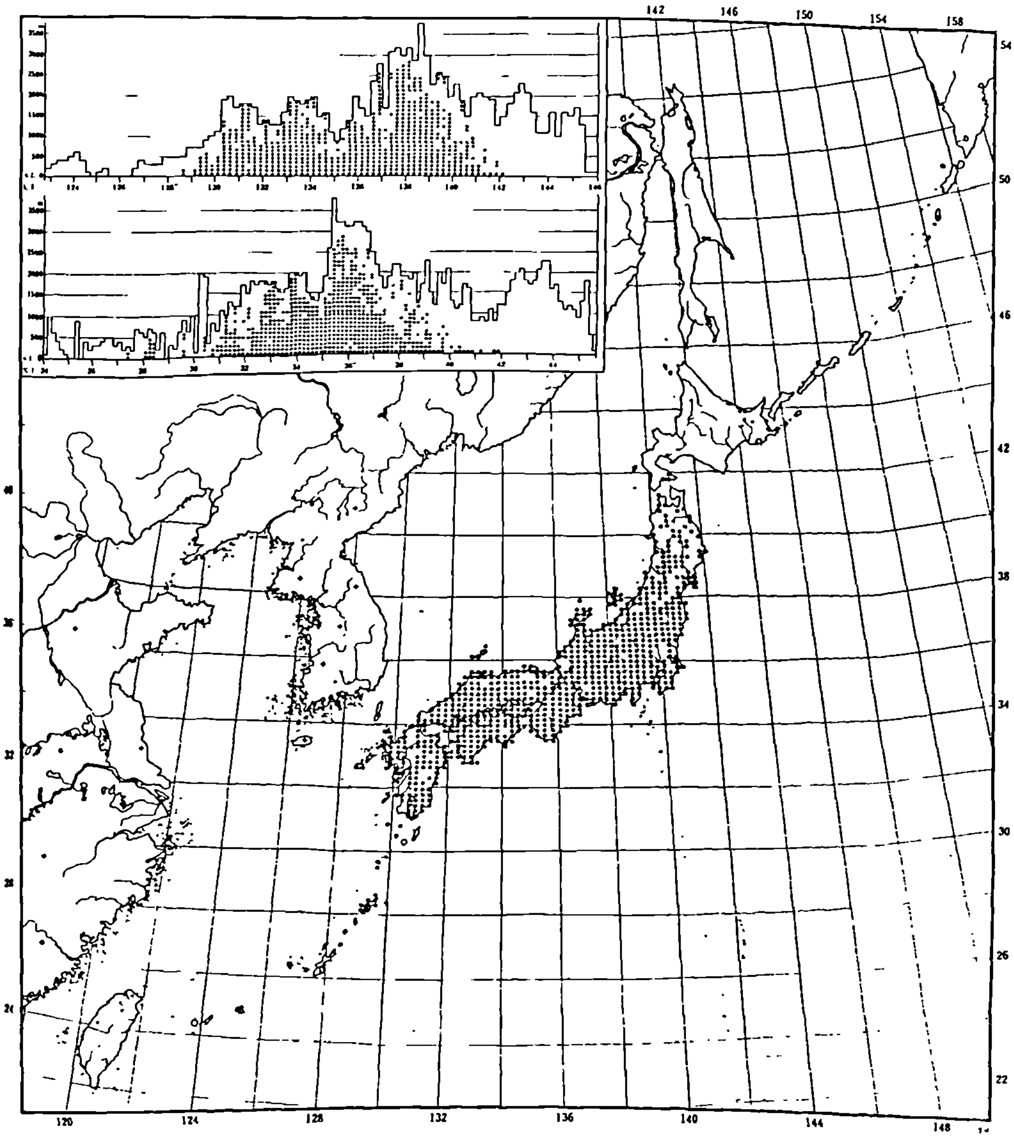


Figure 1.4 Distribution of *F. japonica* in its native range. Each dot represents at least one record in a geoquadrat (each measuring 10 minutes in latitude and 15 minutes in longitide). Localities outside Japan are represented by +. Inset shows W-E and S-N profile of distribution. Source: Horikawa (no date).

F. japonica in Japan is dioecious, that is to say it produces male and female flowers on separate plants. The major means of dispersal is by seed which is produced prolifically in late autumn although vegetative regeneration does occur. Seedling survivorship has been studied by Maruta (1976; 1983; 1994) who found that in order to survive the winter, seedlings needed to achieve a minimum size of 40 mg dry weight. Maruta's studies have been conducted on the slopes of Mount Fuji where *F. japonica* is an important component of the primary succession process from bare volcanic gravels and ash through to establishment of vegetation. *F. japonica* is gradually replaced in the successional process by a tall grass, *Miscanthus oligostachyus* and other species (Tateno and Hirose, 1987) which establish within the patch of *F. japonica* where nitrogen reserves have been accumulated (Adachi *et al.*, 1996a; 1996b). *F. japonica* has the ability to tolerate low nutrient soils with poor water retaining capacity due to its extensive rhizome system. The nitrogen accumulation capacity of the plant has been described by Adachi *et al.* (1996c) and Hirose (1984; 1986; 1988); Hirose and Tateno (1984); Hirose and Kitajima (1986) and Tateno and Hirose (1987).

However, there are a wide range of varieties of *F. japonica* in Japan. Most varieties are classified under the broad type *Polygonum cuspidatum* or *Reynoutria japonica* in the Japanese literature which makes comparisons with plants in the British Isles difficult. Certainly, the plant which is observed in the British Isles is a much taller, more vigorously growing plant than that observed in Japan (Sukopp and Starfinger, 1995.). The majority of the literature describing research on *P. cuspidatum* (or *R. japonica*) in Japan deals with the variety *F. japonica* var. *compacta* (Adachi, pers. comm.). Variation in leaf size, shape and texture, flower colour, plant height and location was noted from personal investigations of herbarium specimens of *P. cuspidatum* and *R. japonica* in Japan at the Makino Herbarium, Tokyo Metropolitan University and the Tsukuba Herbarium. Some of the variants are shown in Figure 1.5. Table 1.1 shows the range of forms, their common Japanese names and their distinguishing morphological characteristics.

(a)

(b)

Figure 1.5 Two varieties of *F. japonica* in Japan. (a) red flowered variety (forma *elata*) and (b) white flowered variety on the slopes of Mt. Hoei in association with the secondary species *Miscanthus oligostachyus* which is becoming established in the centre of the plant. Photographs courtesy of Naoki Adachi.

Table 1.1 Congeners of *F. japonica* in Japan.

SCIENTIFIC NAME	COMMON JAPANESE NAME	MORPHOLOGICAL CHARACTERISTICS
Polygonum cuspidatum syn *Reynoutria japonica* syn *Polygonum reynoutria* Makino var.. *typicum* Nakai	itadori ("itadori" means strong plant)	
Polygonum cuspidatum forma *elata* Hiyama	Mei getsuo (name of the village where this variety is recorded) Also known as Beni-itadori ("Beni" means red)	A form with red flowers
Polygonum cuspidatum var. *uzenensis* (*F. uzenense*) (Honda) Kitamura	Ke-Itadori a variation which grows on the Japanese Sea side and in Tohoku (North East) District. . ("Ke" means hair)	Stems and leaves are covered in hairs (trichomes). Leaves similar in shape and size to those of *F. japonica* in the British Isles.
Polygonum cuspidatum var. *terminale* Hiyama syn *Polygonum cuspidatum* var. *terminalis* Honda	Hachijo-itadori a variation which grows only on Izu Seven Islands. Hachijo-Jima is the largest island of the seven, located approx. 50 km south of Tokyo.	Dark green leaves with a waxy surface.
Polygonum cuspidatum var. *hastatum*		Spear-shaped leaves.
Reynoutria japonica var. *penduliflora*		Pendulous flowers
Reynoutria japonica Houtt. var. *compacta* Hiyama for. *colorans* Hiyama		Pink coloured flowers
Reynoutria japonica var. *compacta* Hiyama	Onoe itadori a variety which grows in alpine regions with short and compact growth habit ("Onoe" means summit)	Leaves have a crinkled margin.
Polygonum sachalinense syn *Reynoutria sachalinensis* (Fr. Schm.) Nakai. syn. *Polygonum sachalinensis* Fr. Schm.	O itadori ("O" means big) Common in northern Japan especially in Hokkaido and the Japanese Sea side of north Japan.	Tall plant (2-3 m) in height with large leaves. Flowers greenish to cream. Large leaves (approx. 15 -30 cm long) Resembling *F. sachalinensis* in the British Isles
Polygonum cuspidatum var. *uzenensis* x *Polygonum sachalinense*	O Ke itadori	Hybrid with hairs (trichomes) on underside of leaves. Resembling *F.* x *bohemica* in the British Isles

The comparison of *F. japonica* in its native and introduced ranges is complex not least because of differences observed in the growth habit, morphological features and genetic constitution of the plant in Japan compared to that in the British Isles (Child and Wade, in prep.). In contrast to the range of morphological differences between *F. japonica* types in their native range, *F. japonica* in the British Isles is much less varied. Although the plant is functionally dioecious, only the male-sterile plant is recorded in the British Isles leading to the suggestion that in the British Isles at least, *F. japonica* is clonal, possibly from a single introduction (Bailey, 1994). The absence of male-fertile plants in the British Isles means that dispersal must be by vegetative spread alone. It is clear therefore that there are significant differences between *F. japonica* in its native range and the British Isles.

1.3.3 The invasion of *Fallopia japonica* in the British Isles

The invasion of *F. japonica* in the British Isles followed some time after its initial introduction. Kowarik (1995a) reviewed a number of invasion studies of a range of plant species (Mack, 1986; Kornas, 1990; Pysek, 1991) and identified two types of time lag phases between the first release of a species for cultivation and the beginning of spontaneous spread. The first type is the time lag between introduction and an escape from cultivation (naturalisation), which is followed by the second type, a time lag between naturalisation and the beginning of a significantly higher rate of population growth. For a number of herbaceous species in Brandenberg, Germany the mean lag time was found to be 131 years between the first observation of a seedling in the area and subsequent spread. For *F. japonica* in the British Isles, the two lag phases were also observed (Figure 1.6). Between the date of introduction and first record of naturalisation, the first lag phase was 36 years. This was followed by the second lag phase (54 years) between naturalisation and beginning to spread spontaneously (Conolly, 1977). Of 184 species studied by Kowarik, only 6% showed a rapid establishment as naturalised species with lag times up to 50 years. Intentionally introduced plants such as ornamental plants have an advantage over those accidentally introduced as cultivation ensures that the initial stages of establishment are achieved successfully. The time lag between establishment and naturalisation is reduced as horticultural species already have a number of established locations from which to spread. This has certainly been the case for *F. japonica* in the British Isles.

Conolly (1977) described four phases in the invasion process of *F. japonica* in the British Isles. The first phase (naturalisation) was the occurrence of primary records of the plant outside the garden environment. The first record of naturalisation was recorded at Maesteg in South Wales in 1886 where the plant was recorded as growing in abundance on cinder tips (Storrie, 1886). This was followed by a pioneer phase of scattered primary occurrences and establishment in many places in and around London and all but two vice counties in Wales. By the 1930s, records had been collected from Scotland, Cornwall, south eastern England and the Midlands, Yorkshire and East Anglia. From 1940, a rapid expansion of the plant was seen with secondary spread from primary foci. This was the beginning of the invasion phase. The final phase is described by Conolly as a consolidation phase with infilling around previously recorded sites.

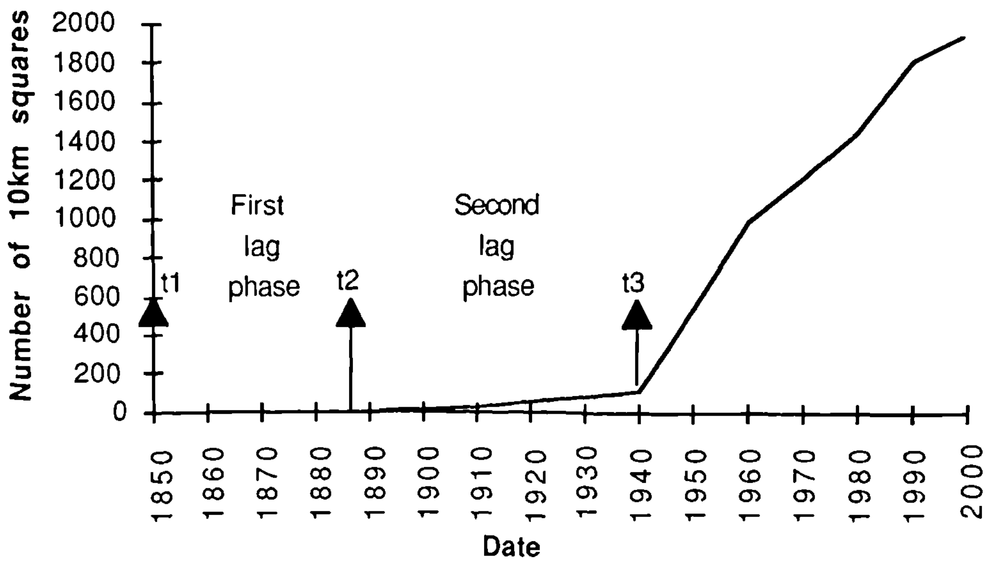


Figure 1.6 Time lags in the invasion of *F. japonica* in the British Isles. The graph shows the first lag phase (t1 - t2) between date of introduction (c. 1850) and first record of naturalisation (1886) and the second lag phase (t2 - t3) between first record of naturalisation and a move towards a significantly higher rate of population growth. Number of 10 km squares in which *F. japonica* is recorded are from Conolly (1977) for records to 1977, thereafter from Biological Records Centre, Institute of Terrestrial Ecology, Monks Wood.

A measurement of successful invasion is given by Elton (1958) and Hengeveld (1989) as the rate of population growth over time or gain in area occupied. From the graph shown in Figure 1.6, it can be seen that the number of 10km squares recording presence of *F. japonica* is still increasing, suggesting that the plant is not only consolidating at previously recorded sites but is also still in its invasive phase. The current distribution of *F. japonica* in the British Isles is shown in Figure 1.7.

1.4 INVASION THEORY

Whether introduced intentionally or accidentally, not all the species which arrive in a region will establish themselves and of those not all will become naturalised. Williamson (1993) suggested that of all species arriving in a new geographic region 10% will become established and of these 10% will become naturalised. This 'tens rule' is disputed by Kowarik (1995b) who suggested that only 5% of total introductions are likely to become established and only half of these will become members of the natural vegetation. He supported this by studies of alien vascular plant studies in Central Europe. This prompts three questions:

1. What properties of a species make it more invasive than others?
2. What physical characteristics of a habitat render it prone to invasion?
3. What are the most appropriate management strategies for the control of invasive plants?

Despite much scientific literature on the subject of plant invasions the answers to these fundamental questions are still elusive (Elton, 1958; Baker, 1986; Vitousek, 1986, Holdgate, 1987; Ashton and Mitchell, 1989; Rejmánek, 1995; Williamson and Fitter, 1996). Similarly, as data on failed invasions are not readily available, the reasons why some introductions fail to become established is still poorly understood (Drake *et al.*, 1989; Rejmánek, 1995; Kowarik, 1995a). In pursuing invasion theory, attempts have been made to isolate common attributes of plants which have become invasive following introduction.

Fallopia japonica

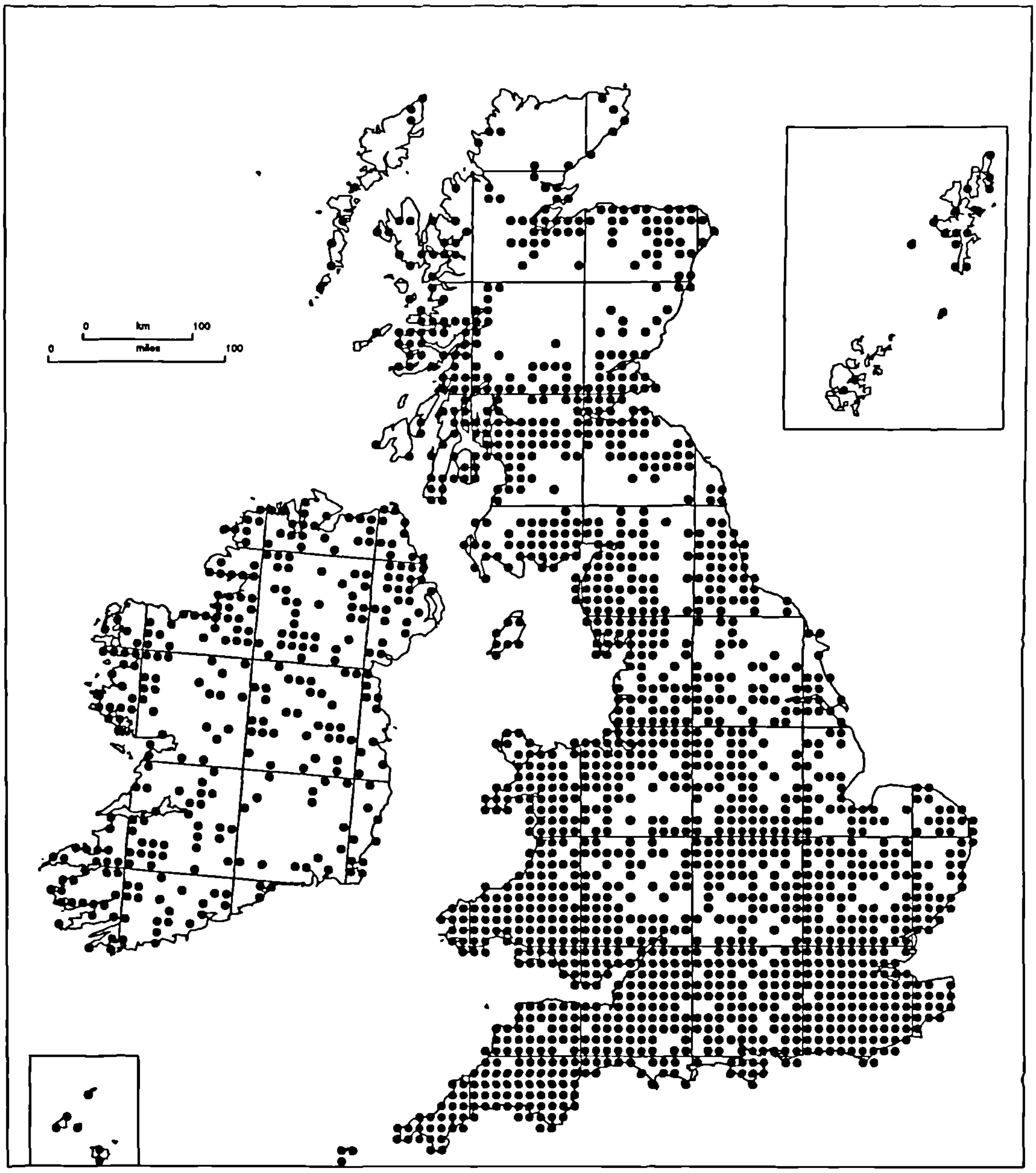


Figure 1.7 The distribution of *Fallopia japonica* in the British Isles 1998. Each dot represents at least one record in a 10km square of the National Grid. Mapped by the Biological Records Centre, Institute of Terrestrial Ecology, Monks Wood.

1.4.1 Properties of *Fallopia japonica* as an invasive species

The best known description of an invasive plant is Baker's (1965) description of the 'ideal weed'. The ideal weed is:

- perennial
- able to germinate in a wide range of physical conditions
- rapidly growing
- early flowering
- self-compatible
- able to produce many seeds which can disperse widely
- capable of reproducing vegetatively
- a good competitor

Similarly, Ashton and Mitchell (1989) characterised those features for aquatic plants which have demonstrated a marked capacity for invasion when introduced to new environments. Significantly, all these factors relate to dispersal and reproductive mechanisms:

- Vegetative reproduction is usually the most common and often the only method of reproduction.
- Human activities are the main mechanism whereby the plant is spread both within and between environments.
- Plants capable of very rapid rates of reproduction often become serious weeds.
- Sexually sterile plants become locally naturalised unless they are purposely spread by humans or possess small vegetative propagules that can be widely spread by other means.

In some respects, *F. japonica* shows the characteristics of Baker's terrestrial 'ideal weed' in that it is perennial, has rapid growth, is capable of regenerating vegetatively and is a good competitor (Beerling *et al.*, 1994). However, in the British Isles, particularly in riparian habitats, the plant displays the characteristics of Ashton and Mitchell's invasive aquatic plant in that as the plant is sexually sterile, vegetative regeneration is the only method of reproduction, it has the ability to regenerate from small vegetative propagules which are widely spread between environments by human activities and is capable of rapid rates of regeneration. The dispersal of *F. japonica* is certainly aided in riparian habitats by the action of water (Beerling, 1991b).

1.4.2 Habitats prone to invasion by *Fallopia japonica*

Since its introduction to the British Isles, *F. japonica* has spread rapidly especially in the south west of England and around conurbations (Conolly, 1977). Although *F. japonica* is rarely observed on agricultural land (pers. obs.), the species has become established predominantly in man made habitats such as spoil heaps, along canal sides, railway embankments (Figure 1.8a and 1.8b), roadsides and cemeteries. *F. japonica* also occurs frequently in riparian habitats (Gunn, 1986; Edmonds, 1986; Beerling, 1991b) and is increasingly recorded in semi-natural habitats and nature reserves (Cooke, 1988). An important factor in the initial stages of an invasion is the role of disturbance. Kornas (1990) described a number of successful plant invasions into Central Europe and divided these into three categories on the basis of their degree of naturalisation:

- those which occur only in man-made plant communities (e.g. urban sites)
- those also established in semi-natural plant communities (e.g. meadows, pastures, disturbed river banks, lake shores)
- those which have succeeded in establishing in entirely natural vegetation.

The advance from one stage to the next becomes progressively more difficult as opportunities to invade disturbed sites become less frequent. In the urban environment or environments disturbed by human activities, opportunities for colonisation become available. In semi-natural sites, the role of natural disturbance e.g. along river banks or lake shores is an important feature in opening sites for colonisation. Human or human related activities such as mowing in meadows or grazing animals on pastures also reduce competition from established plant communities, allowing newcomers to gain a foothold. In natural undisturbed plant communities the availability of these 'safe sites' is reduced and competition for space, light and nutrients from established plant communities reduces the potential for incoming species to establish. Kornas (1990), Kowarik (1990; 1995b) and Sukopp (1998), using case histories of recently introduced aliens in Central Europe, concluded that the process of introduction and naturalisation follows a similar pattern. In stage one, propagules of the plant are accidentally or deliberately introduced to an area and the first individuals appear. This is followed by permanent establishment on

(a)

(b)

Figure 1.8 Typical infestations of *F. japonica* in Swansea, South Wales (a) along a railway embankment (b) adjacent to an amenity area.

severely disturbed sites. In stage three, the plant begins to colonise sites which are subject to a lesser degree of disturbance and finally, stage four, the plant succeeds in penetrating into undisturbed sites. Plants which are introduced as ornamental plants and subsequently escape into the wild enter the process at stage three having been cultivated through stages one and two. Following the 'tens rule' (Williamson, 1993) only a small percentage of introduced species achieve stage four. *F. japonica* in the British Isles has successfully achieved this.

1.4.3 Management strategies available for the control of *F. japonica*

Following the guidelines of invasion theory, once the traits of the plant and the vulnerable habitats have been identified the third aspect of importance in tackling an invasion is the control and management of the species. In the management of *F. japonica*, currently there are two types of control methods available. These are chemical and cultural (mechanical) methods. As yet, no biological control agent has been identified for *F. japonica* although young shoots of the plant are palatable to cattle, horses, sheep and goats (Beerling, 1990a)

Chemical Control

When selecting a herbicide for chemical treatment of a plant species, it is necessary to ensure that the mode of action of the herbicide is appropriate for the plant being treated and that the herbicide is approved for use in the situation in which the plant is growing. As *F. japonica* is a perennial plant growing from an extensive rhizome system, the target for chemical treatment is the below ground part of the plant. It is necessary, therefore, to select a translocated herbicide where application of the product to the leaves will result in translocation of the chemical to the rhizome.

Under the Control of Pesticides Regulations (1986) the use of herbicides in riparian areas is restricted. Eight products have been approved for use near water courses (Ivens, 1993) and of these, five have been tested in field trials for the control of *F. japonica*. Of these, two are recommended for the control of *F. japonica*; these are glyphosate and 2,4-D amine. However, as glyphosate is a non-selective herbicide, other plant species which may be valuable in preventing soil erosion following removal of *F. japonica*, e.g. grasses, are also killed. 2,4-D amine is selective for broad leaved plants and has also achieved some control of *F. japonica* (Beerling, 1990). A survey of control methods practised by the Welsh Water Authority (Beerling and Palmer, 1994) found that the most popular herbicide used was glyphosate, but this was considered to have a limited success. Edmonds (1986) recommended an application of granular dichlobenil before shoot emergence in March, or three applications of glyphosate, firstly when the plant is actively growing and has a large leaf area (early - mid June), then three to four weeks later and finally in late September before the first frosts, when the plant is actively translocating nutrient reserves to the rhizomes for winter storage. Gunn (1986) carried out trials using glyphosate and 2,4 - D amine at different concentrations and times. Whilst all treatments had an effect he found that multiple applications of glyphosate were the most effective although he was unable to determine which concentrations or timings were the most successful. Scott (1988) recommended applying glyphosate in late July when the onset of senescence ensures that the glyphosate is translocated effectively. Beerling (1990b) carried out trials using 2,4-D amine and glyphosate and found that initially 2,4-D amine was more effective at reducing plant biomass but by the end of the season glyphosate had also achieved good control. He recommended two applications of 2,4-D amine, one early in the season (May) to reduce the vigour and height of the *F. japonica* and the other in mid-season (July) to achieve control. Roblin (1988) and de Waal (1995) both recommend that treatment with glyphosate should be continued for a number of years before complete control is achieved.

There is a wider choice of herbicides for use where plants do not grow in the vicinity of water courses. The selective herbicide picloram, not approved for use near water under the Control of Pesticides Regulation (1986), has been found to be successful when sprayed early in the season (Cooke, 1988 and Scott and Marrs, 1984). This herbicide may only be used where there is no risk of drainage to water courses or non-target areas as lateral migration through soil can occur. Picloram is a persistent herbicide which delays planting of replacement vegetation for a period of up to 2 years. Harper and Stott (1966) achieved control using high levels and repeated applications of bromacil. Unfortunately, the test site remained bare for the following two years. They also obtained control using a single foliar spray of picloram in June, which effectively killed the rhizomes of *F. japonica* and reported that a grass sward developed at the site within a year. They found that using the granular formulations of bromacil and picloram was less effective than using sprays. Scott and Marrs (1984) carried out trials with nine herbicides over a two year period; of these picloram was the most effective even when applied once early in the season. Glyphosate was increasingly effective with time and was recommended where risks of run off were anticipated and a slower rate of control was acceptable.

Control work in North America includes a short note from Ferron (1966) who recommended cutting the first growth down before the end of June, then applying Tordon (picloram) to the young re-growth. Ahrens (1975) found that glyphosate killed the stems and leaves after at least two applications, but that the roots remained and were subsequently able to produce shoots. Lynn *et al.* (1979) achieved 100% control of *F. japonica* within 100 days of application, after spraying with glyphosate in the summer. Figueroa (1989) sprayed *F. japonica* colonies adjacent to both paved and unpaved roads and found imazapyr to be the most effective herbicide. Glyphosate achieved some control on colonies adjacent to the paved roads, but colonies by the unpaved roads were covered in road dust which was considered to reduce the effectiveness of glyphosate. He suggested that better control may be achieved by treating plots before mid-summer, when they reach their maximum height, and that repeated application of glyphosate would be more effective.

Hawke and Williamson (1995) recommended herbicidal control as the most cost effective method of control for *F. japonica*. They suggested using picloram in the spring or dicamba, triclopyr, 2,4 - D amine or glyphosate during active growth (July - end of September), the choice of chemical depending on the location of the infestation. What is clear is that the many trials conducted on *F. japonica* have all come to the same conclusion, effective control of *F. japonica* is only achieved when herbicide is applied over a period of several years (Richards, Moorehead and Laing Ltd., 1990; Gritten, 1990; Child *et al.*, 1992; de Waal, 1995).

Mechanical control

In areas of high ecological value, where the use of herbicides is thought to be unsuitable, manual methods of control have been used. Richards, Moorehead and Laing Ltd. (1990) suggested that using a brush cutter with a circular metal blade with a first cut of spring growth (May - June) followed by a second cut in late summer (September) before the plant starts to die back will suppress re-growth. However, to achieve this control would require cutting annually until no new shoots appeared. Beerling (1990a) cut clumps of *F. japonica* and found that their radius increased more than that of uncut clumps, implying that cutting would increase lateral rhizome growth. Cut clumps also showed an increased stem density (Scott, 1988). Repeated cuttings, hand pulling or digging out of rhizomes have been used with varying degrees of success (Richards, Moorehead & Laing Ltd., 1990; Seiger and Merchant, 1997). Seiger and Merchant (1997) concluded that it is unlikely that *F. japonica* can be eradicated by cutting alone. Flailing *F. japonica* stems as a control method was considered expensive and ineffective by various local authorities in Wales (Beerling and Palmer, 1994). Baker (1988) carried out manual control of *F. japonica* in an SSSI (Site of Special Scientific Interest) and found that the species was effectively eliminated in areas mown at fortnightly intervals and after three years it was eliminated from two small areas by pulling. However, ten years of pulling did not eliminate *F. japonica* from a riverbank. Gregson (1981) reported that pulling up rhizomes in June and August/September in a woodland SSSI for six years did not achieve any lasting control of *F. japonica.* A programme of cutting, uprooting and burning on other sites controlled the spread of, but did not eradicate, this species. Burning has not been found to be an effective method of control (Cooke, 1988) and is not recommended (Scott, 1988). Meade and Locandro (1979) achieved some success by cutting the plant to ground level and covering it with black plastic sheeting; however no data were provided to support this observation. Mowing verges, parks and gardens will suppress *F. japonica* (Child *et al.,* 1992). However, the rhizomes persist in the turf and the plant will again take over when mowing is stopped (Scott, 1988). Jackson and Turtle (1986) removed the whole plant by digging out the rhizomes up to a depth of 2 m and laterally up to 5 - 7 m. Obviously this would not be feasible for large stands of *F. japonica.* Richards, Moorehead and Laing Ltd. (1990) found no combination of treatment method more effective than herbicides alone, except where cutting has made stands more accessible for spraying.

Control by grazing

Beerling (1990a and 1991a) studied the effects of grazing by sheep and cattle. He constructed six 2 x 2 m grazing exclosures in February 1990 in two fields containing about 75 sheep and 10 cattle per hectare and observed both reduced shoot densities and shoot height in grazed areas ($p < 0.005$). However control by grazing could only be achieved if the animals were allowed to graze the *F. japonica* for the whole of the growing season. Grazing should be commenced early in the year before the plants get too tall and cannot be cropped efficiently (Beerling and Palmer, 1994). Emery (1983) and Briggs (1991) observed that sheep and goats will graze young shoots until mid-June and that dead stems are a deterrent to animals, restricting easy access to young shoots.

Management

In conclusion, one of the major factors in the continued spread of *F. japonica* in the British Isles has been the difficulties involved in successfully managing infestations of the plant. Control to date has been carried out on an *ad hoc* basis rather than managing the plant in an area through an integrated strategy. Neither chemical nor mechanical methods, normally effective against problem plants, are sufficient to eradicate *F. japonica* easily. Control measures available are not effective unless carried out consistently over a number of years. The cost of control of plants in terms of both human resources and material costs has lead to the unchecked growth of *F. japonica*, especially in areas of low economic value. By allowing *F. japonica* to grow in areas such as waste ground, road verges, railway embankments and along river corridors, a focus for further spread of the plant has been effectively encouraged. Many of the management practices currently used in routine maintenance programmes are effectively spreading the plant to new areas. For example, road verge cutting does not differentiate between plant species. Cut fragments of *F. japonica* are left to be blown or washed into ditches and watercourses with the potential for further spread by vegetative regeneration. What is required now is a coherent management policy for the future control of *F. japonica* in both urban and rural situations which prevents further spread and ensures that control efforts are targeted at vulnerable habitats.

1.5 AIMS AND OBJECTIVES OF THIS STUDY

Fallopia japonica has successfully made the transition from an introduced horticultural species to an invasive alien, naturalised in the British Isles. Existing methods of control are not sufficient to halt its increasing distribution. The aim of this thesis is to provide an insight into the successful invasion of the plant and its congeners in relation to present and future management and control in the British Isles.

More specifically, the objectives of this study are to:

- assess the regeneration potential of vegetative fragments of *F. japonica* and its congeners in the British Isles in order to understand their invasive potential
- assess the extent to which hybridisation occurs between *F. japonica* and its congeners to form hybrid plants

- investigate the extent of the distribution of hybrid plants in the British Isles and the distribution patterns of *F. japonica* in an urban environment
- assess the effects of combining mechanical and chemical treatments in controlling *F. japonica*
- explore the use of Geographical Information Systems in formulating management strategies for invasive plant species

Chapter 2 considers the vegetative regeneration properties of *F. japonica.* In its native range, *F. japonica* is dioecious i.e. the plant has separate male and female forms. To date, in the British Isles, no male-fertile plants have been recorded (Bailey, 1989; 1994; 1997). The dispersal of *F. japonica* in the British Isles is therefore considered to be purely by vegetative means. Chapter 2 investigates the regeneration potential of stem and rhizome material through a series of greenhouse trials with a view to establishing the invasion potential of *F. japonica* in the British Isles. In particular, the viability of stem material under both aquatic and terrestrial conditions is considered.

Bailey (1988) described a new phenomenon in the invasion of *F. japonica*, that of the appearance of the hybrid, *F.* x *bohemica* in the British Isles. This hybrid was first described by Chrtek and Chrtková from the Czech Republic in 1983; it has also been studied in detail in Germany by Alberternst (1995). Chapter 3 investigates the potential for hybridisation between *F. japonica* and other introduced members of the *Fallopia* genus (*F. sachalinensis*, *F. japonica* var. *compacta* and *F. baldschuanica*) and estimates the distribution of hybrid plants in the British Isles.

It is not clear whether hybrid plants exhibit similar properties in terms of dispersal strategies to those of *F. japonica.* Although seeds produced by these species have been shown to be viable under laboratory conditions, the establishment of seedlings in the wild has not been reported (Bailey *et al.*, 1995; Bailey *et al.*, 1996) leading to the suggestion that seed production is not a major factor in the dispersal of these species. In order to make meaningful comparisons of invasive potential for this group of species, this study focuses on vegetative regeneration. Chapter 4 examines the potential for vegetative regeneration of stem and rhizome fragments of *F.* x *bohemica* and related taxa *F. sachalinensis* and *F. japonica* var. *compacta* and makes an assessment of the invasive potential of these species in relation to that of *F. japonica* in the British Isles.

In dealing with a problem invasive plant species, such as *F. japonica*, finding an effective control method is of paramount importance. Chapter 5 describes field trials designed to establish a rapid and cost effective method of controlling the plant through a combination of mechanical and chemical methods.

An important step towards dealing with a plant invasion is to gain an accurate assessment of its distribution. The use of Geographical Information Systems as a data storage facility and management tool is explored in Chapter 6. Through a case study of *F. japonica* in the city of Swansea, South Wales, the importance of accurate assessments of plant distribution, co-ordinating control practices and integrating the management of invasive plants into organisational management policy are discussed.

Finally, the outcome of these various studies are discussed in Chapter 7. By integrating the relative invasive potential of *F. japonica* and its congeners with their current patterns of distribution, suggestions are put forward for the future management and control of these species and the need for further research identified.

2.0 THE REGENERATION POTENTIAL OF *FALLOPIA JAPONICA* FROM CUT STEMS AND RHIZOME FRAGMENTS

2.1 INTRODUCTION

One of the major problems associated with *Fallopia japonica* is its invasive nature and in particular its means of dispersal to new sites. In its native range, *F. japonica* is functionally dioecious and is spread by seed. However, Bailey (1989) reported that in the British Isles, all plants recorded to date were male-sterile with no true *F. japonica* seed being set. The primary dispersal strategy for *F. japonica* in the British Isles must therefore be by asexual means through vegetative regeneration. This regeneration is reported to be primarily from rhizomes (Palmer, 1990; Richards, Moorehead and Laing Ltd., 1990: Beerling, 1990a; Child *et al.*, 1992; Beerling *et al.*, 1994) with small fragments, weighing as little as 0.7 g sufficient to establish new plants (Brock and Wade, 1992). In addition, a number of anecdotal observations have reported regeneration from stem material. In the USA, Figueroa (1989) observed new shoots developing from floating stems and Locandro (1973, 1978) observed that even internode stem tissues were capable of producing adventitious roots. In the British Isles, Lousley and Kent (1981) reported the production of new shoots from stems along the River Lyn in North Devon. Conolly (1977) and Beerling *et al.* (1994) also report the production of axillary shoots from floating stems.

Under natural conditions, in the riparian environment for example, dispersal of plant fragments occurs during high water flow (Beerling, 1991b). Underground parts of the plant are broken off from established plants along stream and river banks resulting in fragments of rhizome material being washed downstream with the potential to form new plants. Away from the riparian environment, dispersal requires human assistance. The movement of soil containing fragments of rhizome material, for example during redevelopment, highway construction and landscaping works, has been responsible for spreading the plant to new areas (Palmer, 1990).

In addition, some management techniques used in the control of *F. japonica* have the potential to produce regenerative material. One of the techniques commonly used is cutting or mowing plants at intervals throughout the growing season (Child *et al.*, 1992; Seiger and Merchant, 1997) such cut material has not to date been recognised as a potential means of spreading the plant. However, when plants adjacent to watercourses are cut, there is a risk that cut stem material may be blown or washed into the water to be dispersed downstream. This is a particular problem when flail mowing is used to manage the plant along watercourses as many small fragments of cut stem material are produced. Indeed, the apparent movement of *F. japonica* along non-aquatic linear habitats, for example roads and railways, could also rely on the ability of cut or broken stem material to regenerate. An understanding of the viability of rhizome fragments and cut stem material and the conditions required for optimum regeneration is therefore fundamental to assessing the successful dispersal of *F. japonica* to new sites and informing management decisions. The current study was undertaken to explore this.

2.1.1 Aims and objectives

The aim of this study was to establish viability of the above and below ground parts of *F. japonica* plants, through an assessment of the regeneration potential of fresh rhizome and stem material subjected to a range of environmental conditions. More specifically, the objectives were to:

- assess the regeneration potential of rhizome fragments and cut stems in terms of their regeneration success and subsequent growth
- investigate whether there is a minimum and optimum size of fragment for rhizome regeneration
- investigate whether segments obtained from different positions on cut stems varied in their potential for regeneration and subsequent growth
- investigate the extent to which the relative positions of nodes on the stem influences shoot growth and regeneration from stem nodes
- establish whether environmental conditions influence the regeneration success of cut stems, in particular the extent to which segments regenerate when buried in soil compared to an aquatic medium and the role of light in the promotion of shoot growth from stem material.

The study was carried out in a greenhouse where environmental conditions could be controlled. Greenhouse studies have been used successfully to test regeneration rates for a range of species including *F. japonica*, for example, Brock and Wade (1992) and Brock *et al.* (1995). Dock Gustavsson (1997) used greenhouse conditions to assess the growth and regenerative capacity of *Cirsium arvense* plants, Pino *et al.* (1995) used greenhouse studies to test the regenerative capacity of *Rumex obtusifolius*. The use of a controlled environment such as a greenhouse reduces the risk of disturbance to trials and ensures that environmental conditions such as temperature, light and planting medium can be controlled for all treatments. A controlled environment also reduces the risk of external factors influencing experimental results such as adverse weather conditions or the impact of other plant species, herbivorous animals and insects.

2.2 METHODS

A study of regeneration was carried out on stem and rhizome segments of *F. japonica* between September and October 1992. Methodology followed the procedures described in Brock and Wade (1992) and Brock *et al.* (1995). No differences in stem regeneration potential were reported by Brock *et al.* (1995) between May, June and September trials but senescent stems collected in October failed to produce shoots. Locandro (1973) reported no significant seasonal changes in the viability of rhizomes when observed in May, July and September. The present treatments were designed to coincide with maximum maturity of stems but before senescence was reached.

Observations of stems shooting in water in the wild, led to sections of stem from various parts of the plant (lower, middle and upper stems) being selected for two treatments: buried in a soil medium and floating in water. Beerling (1990a) reported reduced biomass and stem height at shaded compared to open sites. Stem treatments were subjected to two light conditions, 'sun' and 'shade', in order to assess the role of light intensity on subsequent shoot growth. Ambient light was used for the 'sun' treatments, 'shade' treatments were placed below the greenhouse benches away from direct sunlight. Personal observations of mature plants in the wild confirmed that following cutting, new shoots were produced from stem nodes. Following the procedures developed by Brock *et al.* (1995) segments of stem material including two nodes were selected in order to assess the influence of node position on development of shoots.

As Locandro (1973) reported regeneration from internode tissue, a range of lengths of rhizome material were selected for treatment rather than selecting fragments by number of nodes. Rhizome fragments were cut to length, buried in a soil medium and grown on under ambient light conditions. All treatments were continued for a minimum period of 30 days, again following the procedures of Brock *et al.* (1995). To describe the treatments more clearly, separate procedures for the rhizome and stem regeneration studies are presented.

2.2.1 Rhizome treatment

Collection of Material

Rhizome material from fully mature plants was collected at two locations on 31 August and 1 September 1992. One site was a road verge site at Snell's Nook Lane, Nanpantan, Loughborough (National Grid reference SK 504174) and the other in Wales on the floodplain of the River Tawe (National Grid reference SN 712021), north east of Pontardawe. Neither of these sites had been subjected to chemical treatment nor any other known perturbation prior to collection.

Planting and Recording Procedure

Rhizome lengths of similar maturity, measuring approximately 30 cm in length, were cut from intact rhizomes at a depth of 25 cm below the soil surface. Material from the two locations was pooled to be randomly assigned to four groups of fragment length. Rhizome lengths were kept moist between collection and planting in order to avoid desiccation with fragments being cut to length immediately prior to planting. Three replicates of five fragments of rhizomes of 1, 2, 4, and 8 cm lengths were placed in flat planting trays having dimensions of approximately 30 x 40 x 10 cm in a greenhouse on the campus of Loughborough University (National Grid reference SK 524193). The fragments were covered with approximately 1 - 2 cm of vermiculite-potting soil mix (4:1 mix), and kept at daytime temperatures of 22 to 24^{o} C. No additional light was used during the study. All watering was with rain water at room temperature. Data were collected every two to three days throughout the trial, and included date of emergence of shoots, height of stems, and number of leaves per stem. To maintain consistency of measurement, height of shoots produced was measured from soil level to the uppermost node of the shoot, leaf number recorded only those leaves which were fully open at the time of measurement. Observations during harvest at the end of the trial included the presence and abundance of new roots on the regenerating rhizome fragments. The rhizome fragments were planted on 1 September, 1992 and were harvested 42 days later on 12 October, 1992. A summary of treatments is shown in Table 2.1.

Table 2.1 Summary of rhizome treatments

3 replicates of each of 4 levels of rhizome fragment length 1, 2, 4 and 8 cm (N = 60).

TREATMENT - PLANTING											
REPLICATE I				REPLICATE II				REPLICATE III			
1 cm (n=5)	2 cm (n=5)	4 cm (n=5)	8 cm (n=5)	1 cm (n=5)	2 cm (n=5)	4 cm (n=5)	8 cm (n=5)	1 cm (n=5)	2 cm (n=5)	4 cm (n=5)	8 cm (n=5)

2.2.2 Stem treatment

Collection of Material

Stem material was collected on 31 August and 1 September, 1992 from mature plants at two sites, the floodplain of the River Tawe (National Grid reference SN 712021), near Pontardawe, Wales and a road verge site at Snell's Nook Lane, Nanpantan, Loughborough (National Grid reference SK 504174). Neither of these sites had been subjected to chemical treatment nor any other known perturbation prior to collection.

Planting and Recording Procedure

Stem material from complete plants collected from the two sites was pooled and randomly assigned to be divided into segments each having 2 nodes, for lower (L), middle (M), and upper (U) portions of the stems. The lower segments were from the first node above the soil surface to include the next upper node, the middle segments were cut from approximately 0.5 to 1 m heights, and upper segments were taken from over 1.5 m, characterised by that portion of the plant with active branching. Internode length of segments ranged from 11 - 19 cm. Stem material was cut to length immediately prior to planting and 15 stem segments were grouped by portion (L, M, U) with 3 replicates of 5 segments of each length randomly assigned within the treatment medium.

For the buried treatments, two batches of fifteen segments of each stem portion (L, M, U) were planted in flat planting trays having dimensions of approximately 30 x 40 x 10 cm filled with vermiculite and potting soil. The stems were covered with approximately 1.0 cm of vermiculite-potting soil mix (4:1 mix), and kept at daytime temperatures of 22 to 24^{0}C. The *upper* and *lower* nodes (*u, l*) of each stem segment were marked with a plastic garden tag to aid data collection.

In addition, similar studies were carried out on regeneration of segments subjected to an aquatic medium. For these treatments, two batches of 15 segments of each stem portion (L, M, U) as above, were placed in flat planting trays having dimensions of approximately 30 x 40 x 10 cm filled with rain water and kept at daytime temperatures of 22 to 24^{0}C. The trays were kept topped up with rain water throughout the study. Fifteen stem segments of each portion (L, M, U) of stem were randomly assigned to 3 replicates. The *upper* and *lower* nodes (*u, l*) of each stem segment were marked with a non-toxic indelible pen to aid data collection.

Both buried and water treatments were subjected to two light regimes, 'sun' or 'shade'. For 'sun' treatments, ambient light was used, for 'shade' treatments, the planting trays were placed below the greenhouse shelving away from direct sunlight.

All watering was with rain water at room temperature and buried treatments were kept moist. Data were collected throughout the trial every 2 - 3 days and included, for each stem node, date of emergence of shoots, height of shoots, and number of leaves per shoot. To maintain consistency of measurement, height of shoots produced was measured from soil level to the uppermost node of the shoot for buried treatments and from the point of emergence from the stem to the uppermost node of the shoot for the water treatments. Leaf number recorded only those leaves which were fully open at the time of measurement. Observations during harvest at the end of the trial included the presence and abundance of roots on the regenerating stems. Stems were planted on 3 September 1992 and harvested 39 days later. A summary of stem treatments is shown in Table 2.2.

Table 2.2 Summary of stem treatments

Two treatments, BURIED and WATER at 2 levels SUN and SHADE for each of 3 stem segment lengths UPPER, MIDDLE and LOWER (U, M, L) each consisting of 2 nodes, *upper* and *lower* (*u, l*). Three replicates of 5 (n = 15) of each segment length were assigned to each treatment. (N = 180).

TREATMENT - BURIED						TREATMENT - WATER					
SUN			SHADE			SUN			SHADE		
U (n=15)	M (n=15)	L (n=15)	U (n=15)	M (n=15)	L (n=15)	U (n=15)	M (n=15)	L (n=15)	U (n=15)	M (n=15)	L (n=15)
u l	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*

Statistical analyses

Following collection, data were entered onto Excel spreadsheets and mean percentage regeneration rates were calculated for each of the treatments. Data for shoot height were transformed ($\log_{10}$) to equalise variances according to Day and Quinn (1989) and where appropriate were subjected to Analysis of Variance using Statview 4.5 (Abacus Concepts Inc., 1992-95). Where significant differences were indicated ($p < 0.05$) Fischer's protected least significant difference (plsd) test was calculated to aid mean separation (Steel and Torrie, 1980).

2.3 RESULTS

2.3.1 Rhizome treatment

Regeneration potential

Regeneration of shoots of *F. japonica* from the various rhizome fragments are shown following the greenhouse harvest (Figure 2.1). The mean percentage regeneration success for planted rhizomes of 1, 2, 4 and 8 cm lengths is shown in Figure 2.2.

Figure 2.1 Shoot regeneration from 8, 4, 2 and 1 cm lengths of rhizome fragments at harvest (42 days after planting).

Regeneration of shoots was first observed in 4 and 8 cm lengths 12 days following planting. At 18 days after planting, shoots were observed from 2 cm lengths. Shoots were not observed from 1 cm lengths until 24 days following planting.

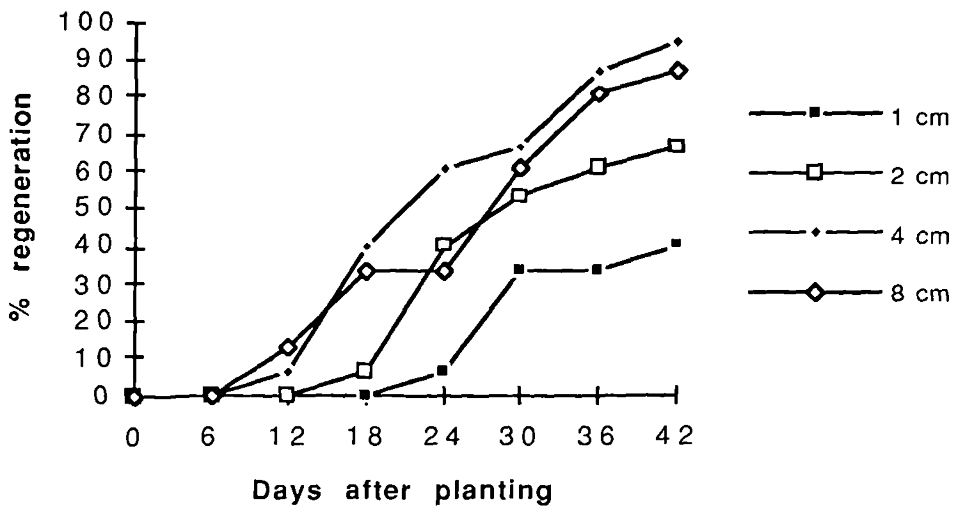


Figure 2.2. Percentage regeneration from planted fragments of rhizome of 1, 2, 4 and 8 cm lengths over the trial period (n = 15 for each fragment length).

From Figure 2.2 it can be seen that a 50% regeneration rate was achieved between 18 and 24 days for 4 cm lengths of rhizome material. For 2 and 8 cm lengths a 50% regeneration rate was achieved between 24 and 30 days. The 1 cm lengths failed to reach a 50% regeneration rate, only achieving a 47% success rate for shoot production by the harvest date (42 days after planting). However, 73.3% of 1 cm fragments had produced roots by the harvest date.

Over the trial period (42 days), 4 and 8 cm fragments of rhizome material had achieved a 94% success rate in producing shoots at harvest, 87% had also produced leaves. At harvest, 93% of 2 and 4 cm lengths and 100% of 8 cm rhizome lengths had produced roots.

Shoot height

In terms of shoot height, no significant differences were found between mean height of shoots produced by 1, 2, 4 or 8 cm fragment lengths until 24 days after planting (Figure 2.3). At this stage, mean shoot height produced by 8 cm lengths was significantly ($p < 0.05$) greater than that produced by 1, 2 or 4 cm fragments. This trend was repeated 36 days after planting. At harvest, no significant difference in mean shoot height was recorded between fragment lengths although 8 cm lengths produced taller shoots than 1, 2 or 4 cm lengths. A summary of shoot height produced from each length of rhizome fragment is shown in Table 2.3.

Leaf number

The number of leaves per shoot produced from planted rhizomes followed the trend for shoot height. Leaf number produced by 8 cm lengths was significantly greater (mean = 3.4 ±0.4; $p < 0.05$) than that produced by 1 or 2 cm lengths at 36 days after planting, although the 4 cm lengths had produced the greatest number of leaves at this stage (mean = 3.6 ±0.2). By harvest (42 days) 8, 4, and 2 cm lengths had produced significantly more leaves than 1 cm lengths (mean = 3.7 ±0.5; 3.5 ±0.3; and 3.2 ±0.2) respectively ($p < 0.05$).

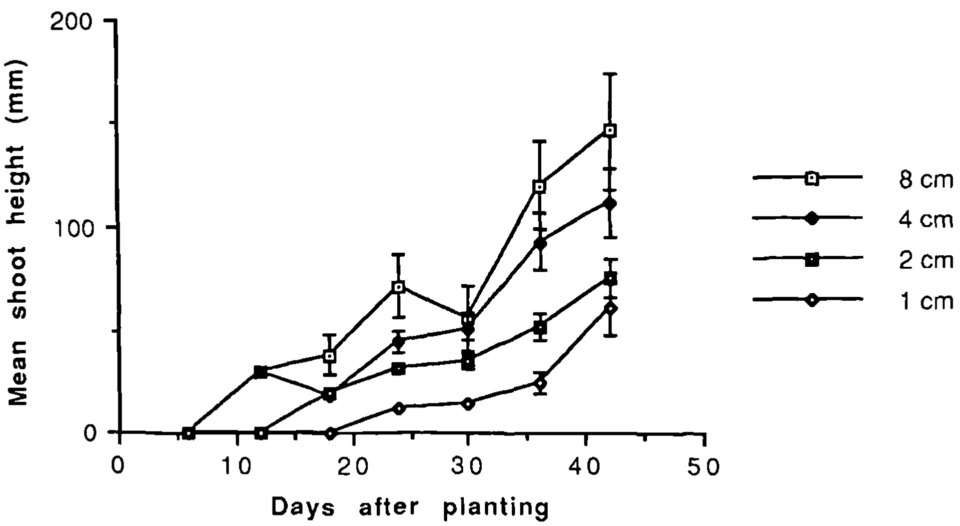


Figure 2.3 Mean shoot height recorded from planted rhizome fragments of 1, 2, 4 and 8 cm lengths over the trial period.

Data presented are mean values ±1SE from 3 replicates of 5 samples, n = 15.

Table 2.3 Height of shoots (mm) produced by different fragment lengths of *F. japonica* rhizome throughout the trial. Data presented are mean values ±1SE from 3 replicates of 5 samples, n=15. For each column, mean values followed by the same letter are not significantly different ($p < 0.05$) using the least significant difference (lsd) statistical comparison.

Rhizome length	6 days	12 days	18 days	24 days	30 days	36 days	42 days Harvest
1 cm n = 15	-	-	-	12.0±^{a}	15.0±^{a}	25.0 ±5.0^{a}	61.5 ±13.55^{a}
2 cm n = 15	-	-	20.0±	31.5 ±2.06^{b}	35.8 ±4.64^{a}	52.8 ± 6.67^{b}	76.0 ±9.18^{a}
4 cm n = 15	-	30.0±	*17.76±	44.1 ±5.19^{b}	51.5 ±5.92^{a}	93.1 ± 14.02^{bc}	112.1 ± 17.14^{a}
8 cm n = 15	-	30.0±	38.5±	70.8 ±15.24^{c}	*55.6 ±16.67^{a}	120.8 ± 21.72^{c}	147.5 ± 28.02^{a}

* Decrease in mean shoot height due to shoot death

2.3.2 Stem treatment

Regeneration potential

Shoot emergence was recorded at day 5 for both water treatments, day 8 for buried shade treatment and day 11 for the buried sun treatment. Stems subjected to water treatments showed a greater initial regeneration success than those stems subjected to buried treatments (Figure 2.4). The water sun treatment showed a 62% success rate at 6 days and water shade treatment 78.6% success by 12 days. Buried treatments showed a slower rate of regeneration success with the buried sun treatment achieving 50.6% success at 30 days and buried shade treatment achieving 66.5% success at harvest (39 days).

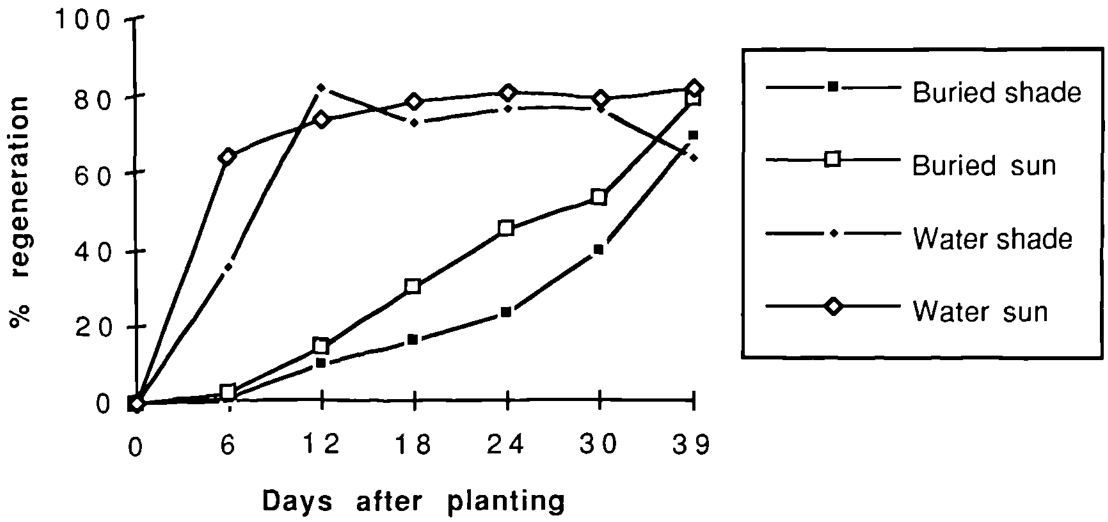


Figure 2.4 Percentage regeneration success from *F. japonica* stems subjected to four treatments over the trial period (39 days).
Data presented are pooled for segment and node, 3 replicates of 15 stems (for each of Upper, Middle and Lower segments) for each node (*upper* and *lower*) for each treatment (N = 360).

Results for the regeneration success of the various stem segments (U, M, L) subjected to these treatments (Table 2.4), show that the greatest regeneration success was achieved by upper segments in the water shade treatment (both *upper* and *lower* nodes) which achieved 100% regeneration success by harvest (39 days). A 50% regeneration rate was achieved by harvest for all stem segments in all treatments apart from upper segment *lower* nodes subjected to the buried shade treatment which only achieved 34% success by harvest.

In order to establish which stem segment length responded most rapidly in terms of regeneration success, the percentage regeneration for each treatment was calculated by stem segment and node. The results are presented in Figures 2.5 to 2.8. The time taken to achieve a 50% regeneration success for the various stem segments (U, M, L) subjected to the buried and water treatments are shown in Table 2.5. Figures 2.5 - 2.8 and Table 2.5 show that the treatment which produced the most rapidly regenerating stems was the water sun treatment (Figure 2.5). For all stem segments and all nodes apart from the lower segment (upper node), 50% regeneration success was achieved within 6 days.

Table 2.4 Percentage regeneration success at harvest (39 days) by stem segment (Upper, Middle, Lower) and node (*upper*, *lower*) for *F. japonica* stems subjected to two treatments (Buried, Water) at two levels (sun, shade). Data presented are percentage of stems which produced shoots for 3 replicates of 5 of each stem segment (Upper, Middle, Lower) subjected to each treatment.

		TREATMENT			
SEGMENT	NODE	BURIED SUN n = 90	BURIED SHADE n = 90	WATER SUN n = 90	WATER SHADE n = 90
Upper	*upper*	87	60	94	100
Upper	*lower*	74	34	94	100
Middle	*upper*	94	100	87	100
Middle	*lower*	87	94	87	94
Lower	*upper*	80	94	80	94
Lower	*lower*	94	54	94	80

Table 2.5 Time taken to achieve 50% regeneration success by stem segment (Upper, Middle, Lower) and node (*upper*, *lower*) for *F. japonica* stems subjected to two treatments (Buried, Water) at two levels (sun, shade).

		TREATMENT			
SEGMENT	NODE	BURIED SUN n = 90	BURIED SHADE n = 90	WATER SUN n = 90	WATER SHADE n = 90
Upper	*upper*	39 days	39 days	6 days	12 days
Upper	*lower*	39 days	-	6 days	6 days
Middle	*upper*	18 days	30 days	6 days	6 days
Middle	*lower*	30 days	30 days	6 days	12 days
Lower	*upper*	30 days	30 days	12 days	12 days
Lower	*lower*	30 days	-	6 days	24 days
Mean for all segments and all nodes (n = 90)		31 days	32 days	7 days	12 days

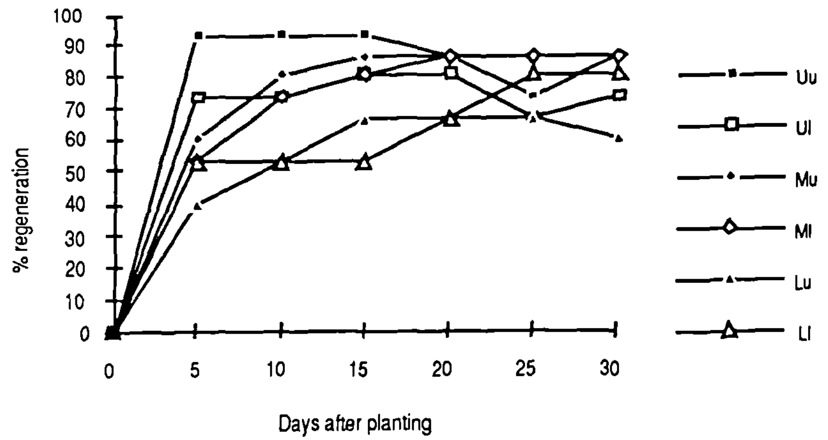


Figure 2.5 Percentage regeneration success by stem segment and node for water sun treatment (n = 15)

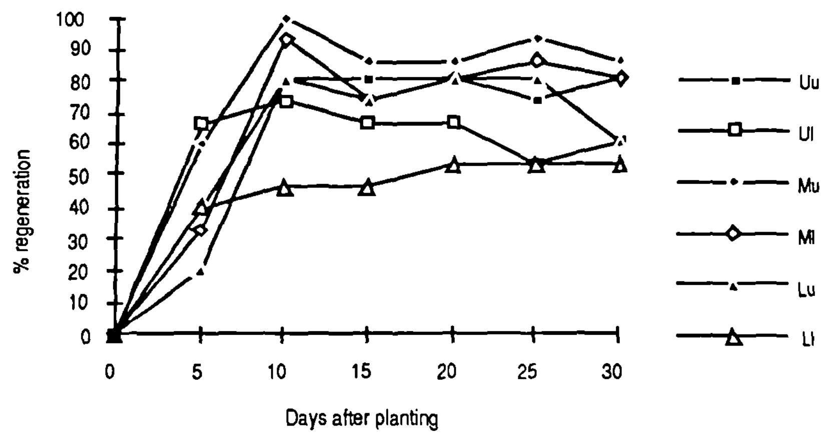


Figure 2.6 Percentage regeneration success by stem segment and node for water shade treatment (n = 15)

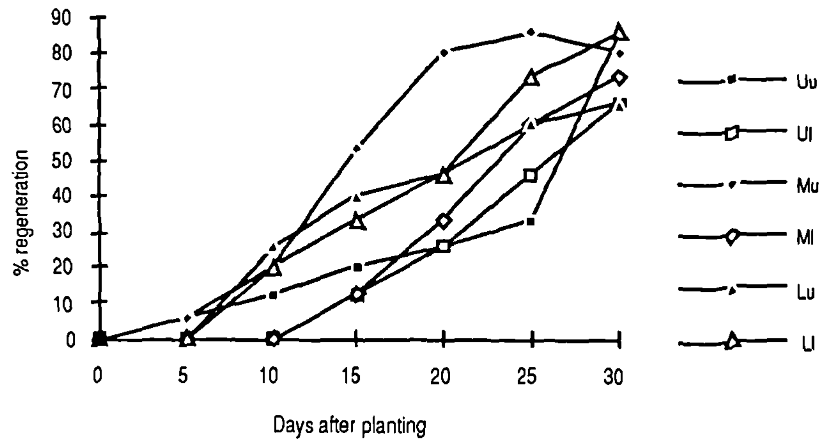


Figure 2.7 Percentage regeneration success by stem segment and node for buried sun treatment (n = 15)

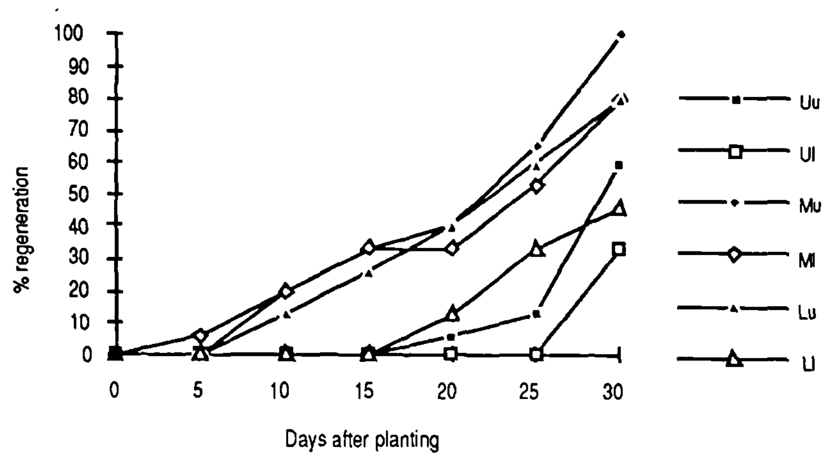


Figure 2.8 Percentage regeneration success by stem segment and node for buried shade treatment (n = 15)

For the water shade treatment (Figure 2.6), upper segment (lower node) and middle segments (upper node) achieved the same level of success. A slightly longer period of 12 days was required for upper and lower segments (upper nodes) and middle segments (lower node). Lower segments (lower node) required 24 days before 50% regeneration was achieved.

For the buried sun treatments (Figure 2.7), a 50% regeneration rate was achieved for middle segments (upper node) by 18 days. For the remaining middle segments and lower segments (both nodes), the time required was 30 days, for upper segments (both nodes) 50% regeneration was not achieved until harvest (39 days).

In the buried shade treatment (Figure 2.8), the middle segments (both nodes) and lower segments (upper nodes) achieved 50% regeneration success by 30 days. Upper segments (upper nodes) did not achieve 50% regeneration until harvest (39 days) upper and lower segments (lower nodes) did not achieve 50% regeneration within the trial.

Root regeneration from stem treatments
At harvest (39 days after planting), stems were examined for the presence of roots. The results are presented in Figure 2.9. Buried sun treatments produced a higher mean percentage regeneration of roots for upper segments although middle segments subjected to the buried shade treatment produced a higher percentage regeneration overall. In shade treatments, middle segments produced the greatest percentage regeneration of roots at the end of the trial. Buried treatments produced a greater percentage of stems with roots than water treatments Figures 2.10 and 2.11 show shoots and roots produced by stems subjected to buried sun and water sun treatments during the trial.

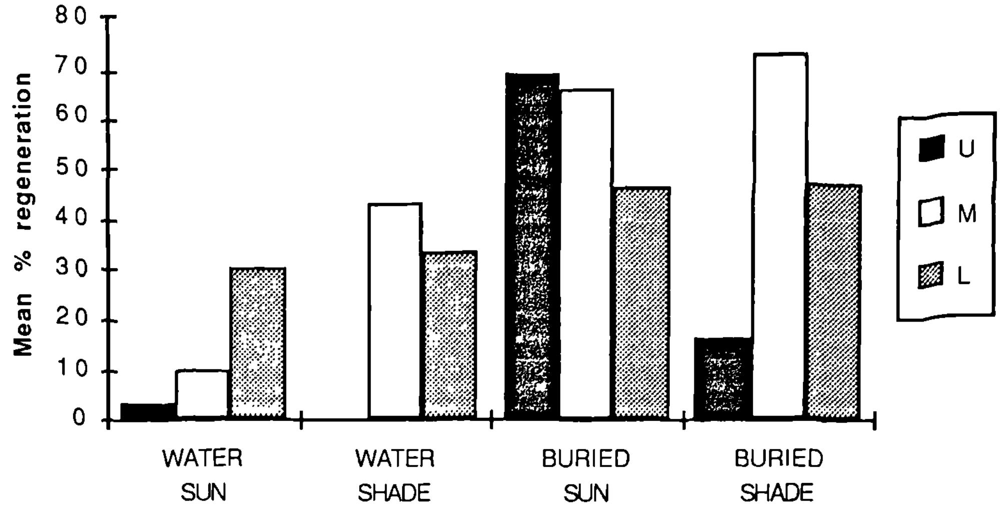


Figure 2.9 Percentage regeneration of roots at harvest (39 days after planting) from stem segments subjected to two treatments (Buried, Water) at two levels (sun, shade). Data presented are pooled from 3 replicates of 5 segments subjected to each treatment.

Flower production from stem treatments

Throughout the trial, a number of stems were observed to be producing shoots bearing flowers. The percentage of stems which successfully produced flowering shoots by harvest (39 days after planting) is shown in Figure 2.12. Stem segments subjected to the water sun treatment produced a greater percentage of flowering shoots for all segments. In general, upper segments produced a greater percentage of flowering shoots than middle segments. In the buried shade treatment, only middle segments produced shoots with flowers. Flowering shoots were only produced by lower segments in the water sun treatment.

Figure 2.10 Shoot regeneration from stem subjected to buried sun treatment after 30 days. Note extensive root system from lower node.

Figure 2.11 Shoot regeneration from stems subjected to water sun treatment at harvest. Note presence of flowering shoots and roots from lower node of upper stem segment on the far right of the photograph.

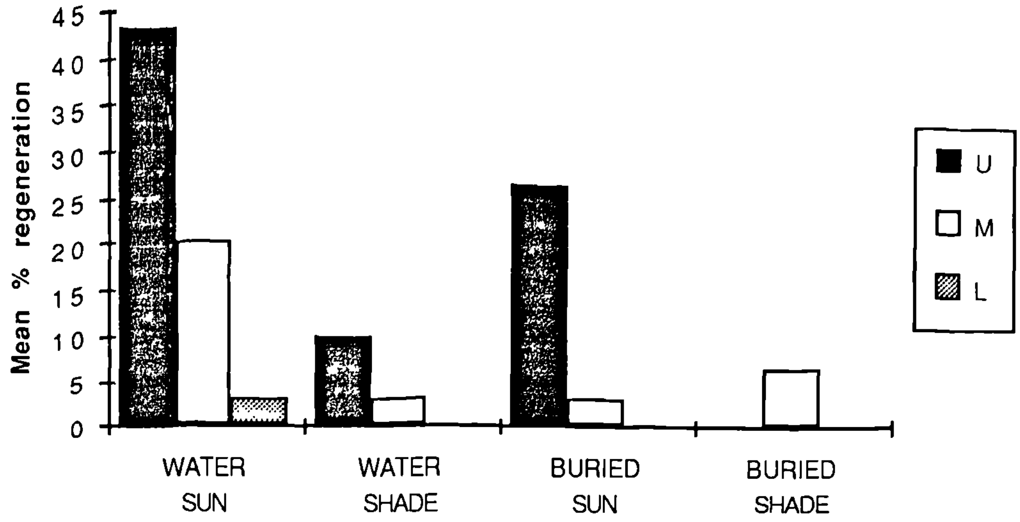


Figure 2.12 Percentage regeneration of flowers on stems subjected to two treatments at two levels at harvest (39 days after planting). Data presented are pooled from 3 replicates of 5 segments subjected to each treatment.

Shoot height

Results of the height of shoots produced by stems subjected to each of the four stem treatments are shown in Figure 2.13. Initially, at 6 days after planting, stems subjected to the buried sun treatments showed significantly greater ($p < 0.05$) shoot height than stems in either of the water treatments (sun or shade). By 12 days, the stems in both buried treatments, (sun and shade) showed significantly greater ($p < 0.05$) shoot height than those in either of the water treatments. This trend continued until 30 days after planting. At this time, stems subjected to the buried shade treatment showed significantly greater ($p < 0.05$) shoot height than those subjected to the buried sun treatment and stems in the water sun treatment greater shoot height ($p < 0.05$) than those in the water shade treatment. At harvest, 39 days after planting, buried shade and buried sun treatments had produced significantly taller shoots than water treatments ($p < 0.05$). Stems subjected to water sun treatments had produced taller shoots ($p < 0.05$) than those subjected to the water shade treatment (Table 2.6).

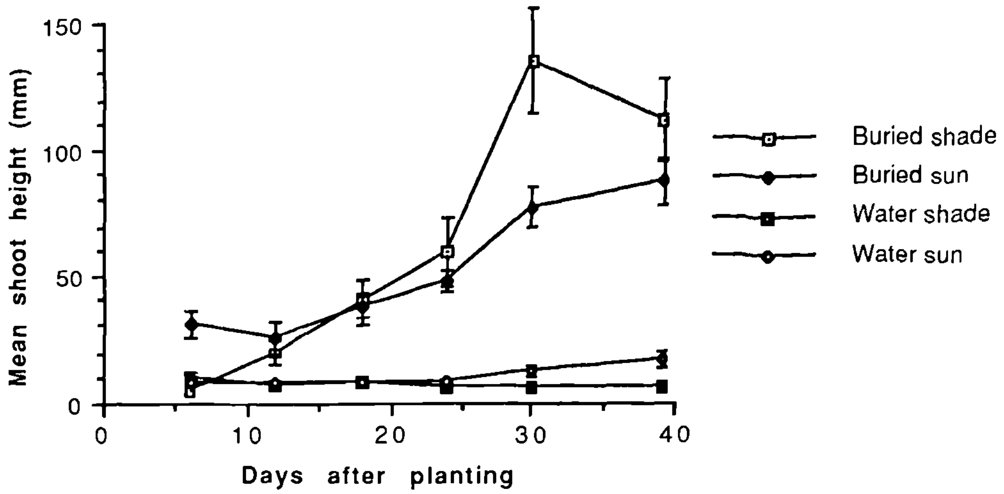


Figure 2.13 Mean shoot height produced by stems subjected to buried and water treatments. Data presented are mean values ±1SE from pooled data for all stem segments subjected to each treatment.

Table 2.6 Mean shoot height at harvest (39 days after planting) for stems subjected to 2 treatments (Buried, Water) at 2 levels (shade, sun). Data presented are mean values ±1SE from pooled data (3 replicates of 5 samples of each segment Upper, Middle, Lower for both *upper* and *lower* nodes). Values followed by the same letters are not significantly different ($p \leq 0.05$) using the least significant difference (lsd) statistical comparison.

	TREATMENT			
	BURIED SUN ($n = 90$)	BURIED SHADE ($n = 90$)	WATER SUN ($n = 90$)	WATER SHADE ($n = 90$)
Mean shoot ht (mm) ±1SE	83.4^{a} ±8.8	105.7^{abd} ±15.4	16.1^{ef} ±3.4	5.7^{cf} ±0.9

Results for shoot height by stem segments (upper, middle and lower) are shown for each treatment in Figures 2.14 to 2.15. No significant differences ($p < 0.05$) were recorded in shoot height produced from either *upper* or *lower* stem nodes throughout the trial for any of the treatments.

Figures 2.14 and 2.15 show that initially there was a delay in shoot production for the buried shade treatment compared to the buried sun treatment. The appearance of shoots was recorded after 6 days in the buried sun treatment but not until 18 days in the buried shade treatment. This was the case for all stem segments (upper, middle and lower).

For the buried sun treatment, 18 days after planting, lower stem segments had produced significantly taller ($p < 0.05$) shoots than upper segments. By 24 days, shoot height was significantly greater ($p < 0.05$) for shoots produced from lower segments than middle and upper segments. This trend continued until harvest (39 days) when significant differences were recorded ($p < 0.05$) between the height of shoots produced by all types of segments.

In the buried shade treatment, there was no significant difference between height of shoots produced by upper, middle or lower segments until 30 days when lower segments produced significantly greater ($p < 0.05$) shoot height than upper segments. By harvest (39 days after planting) significant differences ($p < 0.05$) were recorded between height of shoots produced from all types of segments.

Figures 2.16 and 2.17 show results for shoot height produced by stems subjected to water treatments. For the water sun treatment, initially, 6 days after planting, upper segments produced significantly greater ($p < 0.05$) mean shoot height than lower segments. This trend was reversed and by harvest (39 days after planting) shoots produced by lower segments were significantly ($p < 0.05$) taller than those produced by middle or upper segments.

Water shade treatment shows an initial reduction in shoot height from all stem segments. This was due to early shoot death possibly caused by damping off disease. A similar trend to the water sun treatment was observed in this treatment with upper stem segments producing significantly taller shoots at 12 days than lower segments ($p < 0.05$). By 30 days, middle segments were producing significantly taller shoots than upper segments ($p < 0.05$), a trend which continued to the harvest date.

The buried shade treatment was slow to produce shoots in comparison to the other treatments. This may have arisen from possible differences in soil temperature between sun and shade treatments which could have led to differences in metabolic rates.

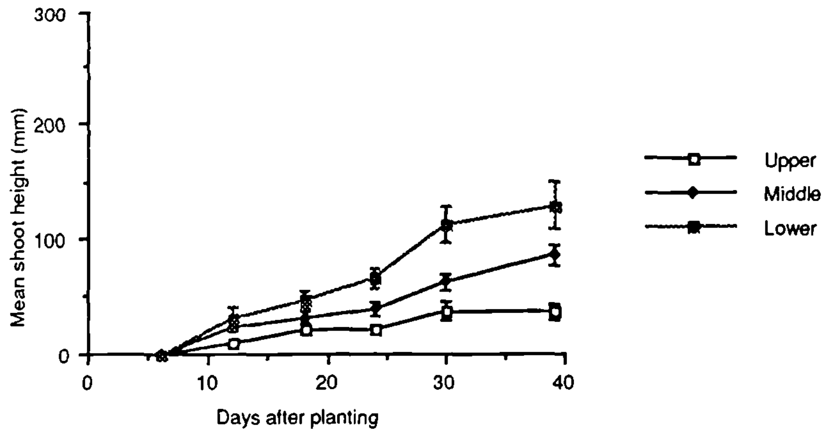


Figure 2.14 Mean shoot height produced by stems subjected to buried sun treatment by segment. Data presented are mean values ± 1SE of 3 replicates of 5 samples of each segment (Upper, Middle, Lower), pooled for nodes.

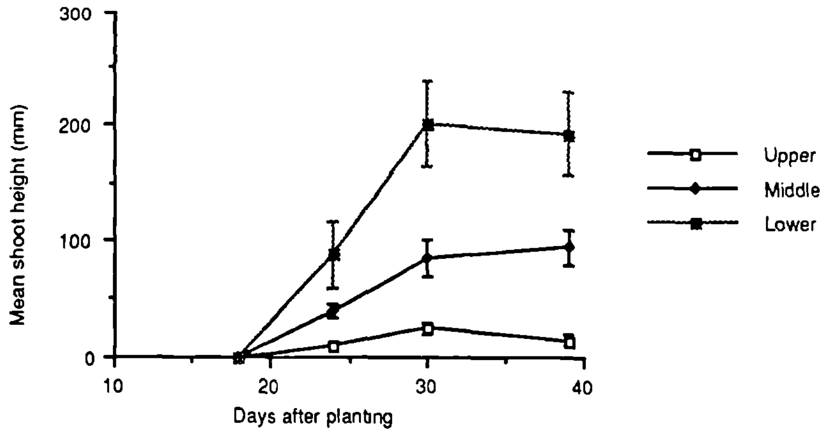


Figure 2.15 Mean shoot height produced by stems subjected to buried shade treatment by segment. Data presented are mean values ± 1SE of 3 replicates of 5 samples of each segment (Upper, Middle, Lower), pooled for nodes.

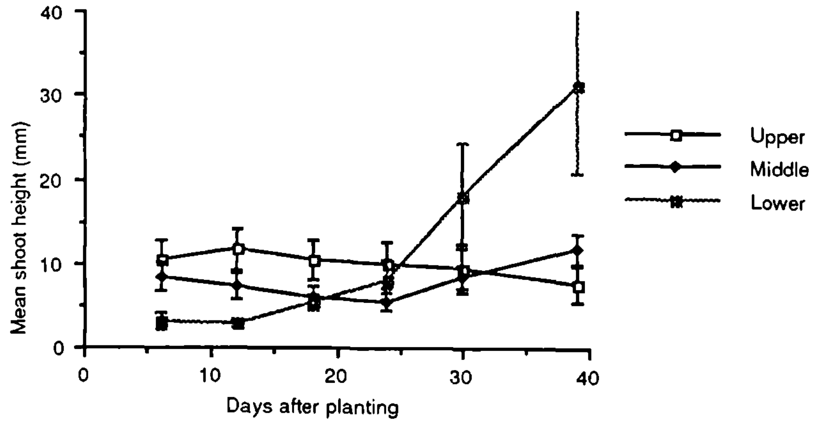


Figure 2.16 Mean shoot height produced by stems subjected to water sun treatment by segment. Data presented are mean values ± 1SE of 3 replicates of 5 samples of each segment (Upper, Middle, Lower), pooled for nodes.

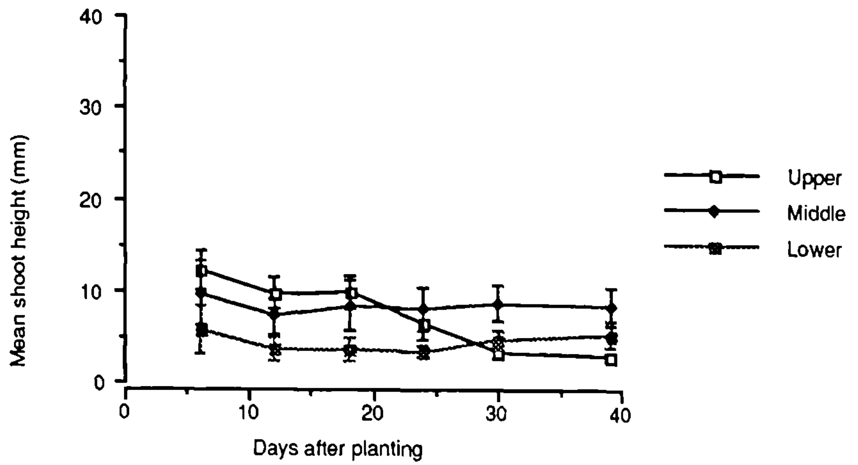


Figure 2.17 Mean shoot height produced by stems subjected to water shade treatment by segment. Data presented are mean values ± 1SE of 3 replicates of 5 samples of each segment (Upper, Middle, Lower), pooled for nodes.

Leaf production

Initially, 6 days after planting, lower stem segments in the water sun treatment produced a significantly greater ($p < 0.05$) number of leaves than upper segments. At this time, the buried treatments had produced no leaves at all. As with shoot height, this trend was reversed by 18 days when leaves produced initially in the water treatments had died. Upper stem segments at 18 days following planting in the buried stem treatments had still not produced leaves. By 30 days, middle and lower stem segments had produced significantly more leaves ($p < 0.05$) than the upper segments and the buried treatments more leaves than water treatments. This trend continued to the harvest date. No significant difference was observed in the number of leaves produced by *upper* or *lower* nodes for any of the segment lengths throughout the trial.

2.3.3 Comparison of rhizome and stem treatments

A summary of regeneration characteristics for stem and rhizome material is shown in Table 2.7. Pooled data for each treatment are presented as ranges of mean values to show the considerable range in regeneration response from rhizome fragments and stems subjected to buried and water treatments. Differences between treatments are marked where significant ($p < 0.05$).

Table 2.7 Comparison of regeneration rates and shoot characteristics for stem segments and rhizome fragment treatments. Data presented are range of mean values from pooled data for treatment, fragment length and stem segment and node. (* denotes significant difference at $p < 0.05$)

PLANT PART TREATMENT CHARACTERISTIC	RHIZOME Buried	STEM Buried	 Water
Days to emergence	12-24	6-24	6
Days to 50% regeneration	18-30	31-32	7-12
% shoots at harvest	47-94	47-97	87-97
% roots at harvest	73-100	16-73	0-43
% flowers at harvest	0	0-26	3-43
Mean shoot height at harvest (mm)	61-147	14-190	2-31*
Leaf number at harvest	2-3	3-21	0-2

A comparison of mean shoot height produced by rhizome fragments and stem treatments is shown in Figure 2.18. Although initially, shoots were produced by the stem treatments by 6 days compared with 18 days for the rhizome treatments, the rhizome treatments resulted in a greater shoot height at the end of the trial period. The data presented in Figure 2.18 are pooled data for all treatments, for rhizome fragment lengths and for stem segments.

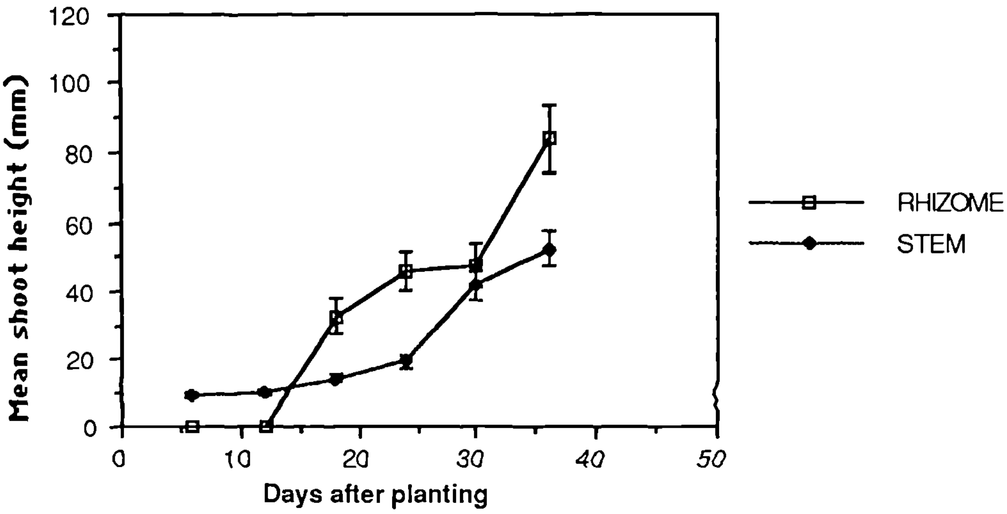


Figure 2.18 Comparison of mean shoot height produced by rhizome fragments and stem segments. *Data presented are pooled mean values* ±1SE for all rhizome and all stem treatments.

2.4 DISCUSSION

Although dispersal of below ground tissues has been regarded as the major factor in the spread *F. japonica* in the British Isles (Beerling, 1990b; Palmer, 1990; Beerling *et al.*, 1994), the results of this study clearly demonstrate that above ground cut stem material also provides a significant method of regeneration.

Brock *et al.* (1995) reported that 68 - 69% of rhizomes produced shoots in three greenhouse studies. When shoots that had not grown sufficiently to reach the soil surface were included, 83% of the rhizome segments had produced shoot tissue. In this study, a mean percentage success rate of 80.5% was recorded for pooled rhizome fragments at harvest. However when fragment size was examined, the smallest (1 cm) rhizome sections provided a 47% success in shoot production, while 94% of the 8 cm lengths successfully produced shoots. Shoot emergence for 4 and 8 cm fragments began 12 days after planting whereas 1 and 2 cm fragments began to produce shoots at 18 and 24 days after planting respectively. These results have identified a relationship between size of fragment and percentage and timing of shoot regeneration from rhizome fragments. Ninety percent of all rhizomes produced new root material by harvest providing evidence of the high viability of rhizomes in the production of new plants. Four centimetre lengths of rhizome material gave the most rapid regeneration response,whilst 8 cm fragments resulted in taller shoots.

Adachi *et al.* (1996b) described the branching patterns of *F. japonica* rhizomes in Japanese material and suggested that rhizomes exhibit apical dominance whilst intact. When this is broken by fragmentation, secondary bud development is enhanced. It is possible that longer fragment lengths do not confer enhanced regeneration potential but do result in taller shoots due to increased reserves of nutrients. In the collection of material, the position of rhizome within the parent plant was not considered as a factor in these trials. Differences reported in translocation of nutrients between peripheral and central rhizomes (Suzuki, 1994b) suggests a regulatory mechanism for rhizome resources which may affect subsequent regeneration rates and shoot development.

On the basis of data derived from greenhouse trials on *Cirsium arvense* and *R. obtusifolius*, both invasive perennial weeds of agricultural land, Pino *et al.* (1995) and Dock Gustavsson (1997) suggested that the amount of energy reserves stored in vegetative fragments and the depth to which the fragments were planted were two of the main factors in competitive growth of these plants. *C. arvense* root fragments planted at depths of 5 cm were more resistant to disturbance, having more reserves than those planted 20 cm deep which had utilised reserves for shoot elongation required to reach the soil surface. This is supported by Locandro (1978) who found that an enhanced rate of regeneration was observed in *F. japonica* when planted at depths of 1 - 2 cm as compared with deeper burial (50 cm). For *R. obtusifolius*, stem fragment regeneration was not observed at planting depths greater than 15 cm (Pino *et al.*, 1995). The present study with *F. japonica* fragments used a shallow planting medium (1 - 2 cm deep) for both rhizome and stem treatments as the treatments were designed to replicate some of the factors in the field relating to dispersal of the plant. A shallow covering of soil or silt following flooding is more likely to occur in field situations than deep burial. In the management of *F. japonica* however, depth of planting is a critical factor when disposing of soil containing vegetative fragments. Current guidelines (Welsh Development Agency, 1998a) recommend a burial depth of at least 2 m to ensure no re-growth.

This study suggests that an aquatic environment is more successful in promoting stem regeneration than a terrestrial environment. In the stem regeneration trials, water treatments were most effective in achieving a 50% regeneration success rate with water sun and water shade treatments taking between 7 and 12 days respectively to reach this level of success. The buried treatments required between 31 and 32 days to achieve 50% regeneration although some segments in the buried shade treatment failed to achieve this within the period of the trial. In *F. japonica*, initiation of new shoots is regulated/ inhibited by apical dominance. It is possible that in the water treatments the hormone responsible is leached from the stems more rapidly than in the buried treatments and therefore allows for a more rapid rate of shoot initiation.

Both the water sun and buried sun treatments required slightly less time to achieve 50% regeneration than the shade treatments. Shade treatments were placed away from direct sunlight and were therefore subjected to lower temperatures than sun treatments, however, Beerling (1991b) and Seiger (1997) observed that plants in shaded woodland did not grow as vigorously as those in unshaded areas. This suggests a light intensity response in *F. japonica* once shoots emerge.

Using data from the treatments in this study it is possible to speculate on the environmental conditions most conducive to regeneration, the size of the propagule and the part of the plant which is most infective. For rhizome treatments, 4 cm lengths gave the most rapid response in terms of regeneration rate and produced shoots which were comparable in height to those produced by 8 cm fragments. For stem treatments, middle segments gave the most consistent rate of regeneration and although slow to regenerate (30 days) in comparison to the water treatments (6 days) did show a consistent increase in shoot height over the trial period. Stems subjected to the buried shade treatments produced the tallest shoots. A comparison of these two treatments is shown in Figure 2.19. Although the stem regeneration takes longer to produce shoots, at 24 days, both stem and rhizome material have reached the same shoot height. In terms of assessing the invasion potential of vegetative material the important factors are the time required for shoot emergence and the probability of regeneration success. Rapid shoot emergence and a high probability of success are indicators of successful establishment.

The rate of shoot increase measured in this study was only 5 to 10% of shoot growth rates reported in the literature. A bulletin from Iowa State University (1980) reported *F. japonica* growth rates of 50 to 100 mm in 24 hours. Wolf (1971) reported a mean shoot increase of 46.5 mm per day. In both cases, the data were from intact stands of *F. japonica*, not from shoots regenerating from rhizome fragments or stem segments as was the case in this study. In this study, the greatest increase in shoot growth was from 8 cm *F. japonica* rhizome segments which had a mean height increase of 10 mm per day 30 to 36 days after planting. In the stem treatments, the most rapid increase in shoot growth was from lower stem segments subjected to the buried shade treatment which had a mean height increase of 11.8 mm per day between 24 and 30 days after planting. This rate of shoot increase agrees with that reported for earlier studies by Brock *et al.* (1995) in greenhouse treatments. Maximum stem height observed in this study was 525 mm at harvest, for a shoot from the buried shade treatment, although the overall mean height of shoots produced was similar to that obtained in previous studies (120mm) undertaken by Brock and Wade (1992) and Brock *et al.* (1995).

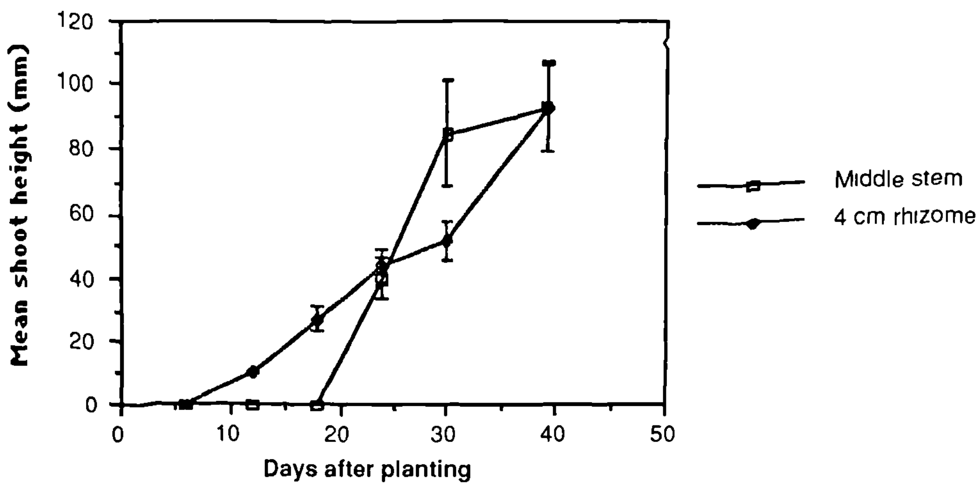


Figure 2.19 Comparison of mean shoot height produced by planted 4 cm rhizome fragments and middle stem segments subjected to buried shade stem treatment. Data presented are mean values ±1SE, data for stem segments are pooled for nodes.

Initially, mean shoot height was significantly greater ($p < 0.05$) for upper segments in the water treatments and for lower segments in the buried treatments ($p < 0.05$). By the end of the trial, lower segments had produced significantly taller shoots over all treatments ($p < 0.05$). The initial extension of shoots from upper segments could be due to the nature of growth of the plant in its mature state. New shoots and leaves are produced by the upper parts of the plant and bud formation could have been initiated before planting. The eventual greater shoot height from middle and lower segments could be due to the larger reserves of nutrients in these segments which would support a sustained increase in shoot height.

Throughout this study, no growth activity was noted on internode tissue except for the development of roots and adventitious root buds on internode material close to nodes in the buried and water treatments. Similar information was reported by Locandro (1978), but the portion of parent stem where the adventitious roots were located was not given.

Flowering shoots were observed in stem treatments but not in the rhizome treatment. The reason for this could have been that the plants were in flower when the stem material was collected and although all leaves and shoots were stripped off before planting, flower buds may already have been initiated in the stem material.

Brock *et al.* (1995) reported that stem regeneration was assessed in *F. japonica* stems harvested in October 1991. These stems produced no shoot growth. It is hypothesised that the stems produced no shoots because of the senescent nature of above ground growth in October. Shoot regeneration was also never realised for stem segments placed on the surface of vermiculite and potting soil mix in the greenhouse, nor from sections of stem internodes It is surmised therefore that there is a requirement for stem material to be fresh and actively growing and that segments are required to contain nodes in order for stem material to provide an adequate shoot regeneration capacity. This has important implications for management in that cut material which is allowed to dry out on site is unlikely to be subject to regeneration. Similarly, once the plant has reached senescence, stem material appears to no longer be productive. Cut material from plants late in the season, once senescence is reached, will therefore not compromise management strategies dealing with the prevention of spread of the plant.

The results of this study show a 35% overall mean of shoots with roots from stem tissue, with buried treatments producing a greater percentage of root regeneration than water treatments at harvest. However, the regeneration rate for water treatments was found in this study to be significantly more rapid than buried stem treatments with water treatments achieving a 50% regeneration rate between 6 and 12 days after the start of the trial and buried treatments after 30 days. The potential for establishing *F. japonica* from stem tissue is therefore significant. This is especially true for stem segments floating in water, a likely dispersal agent for *F. japonica* in riparian habitats. A common management practice in riparian areas is to cut plants during the growing season prior to herbicide application. This enables easy access for operators to spray the regrowth. Fresh cut material left on the banks of streams and rivers, especially after flail mowing, is at risk of being blown or washed into water courses with a high associated potential regeneration risk. The results obtained in this study represent a high potential for spread of the plant by cut stems. The high regeneration potential of stem material subjected to water sun treatments indicated in this study suggests that regenerating stems washed downstream could establish new colonies of *F. japonica* especially if lodged on silt or shingle banks once shoots had been produced.

This study demonstrates that even without viable seeds, *F. japonica* in the British Isles has a very successful strategy for reproduction both by rhizome fragments and cut stems. As no true *F. japonica* seed is set in the British Isles, the production of flowers by upper stem segments in an aquatic medium could be considered to be insignificant in management terms. However, *F. japonica* does hybridise with *F. baldschuanica* and with *F. sachalinensis* and *F. japonica* var. *compacta* to form *F.* x *bohemica* (Bailey, 1989; Bailey *et al.* 1995; Bailey *et al.*, 1996). The availability of potential sources of viable pollen from these related species opens the debate on the spread and dispersal of this group of species. Hybridisation and the distribution of hybrids in the British Isles is discussed further in Chapter 3.

2.5 CONCLUSIONS

The main outcomes of this study are set out below for both rhizome and stem treatments.

Rhizome treatments

- The optimum response to shoot production in terms of early shoot emergence and time required for 50% regeneration was achieved by 4 cm fragments.
- Although 1 cm fragments successfully regenerated, the minimum size of fragment to achieve 50% regeneration success was 2 cm.
- Eight centimetre fragments produced a greater percentage of shoots, roots and leaves at harvest than 1, 2 or 4 cm fragments.
- As rhizome length increased, progressively taller shoots were produced indicating a relationship between rhizome nutrient reserves and subsequent growth potential.

Stem treatments

- An aquatic medium resulted in stem segments showing a more rapid response to shoot production, a greater percentage success rate in shoot production at harvest and a greater number of flowering shoots than a soil medium.
- Stems grown in a soil medium showed a greater percentage success rate for root production, greater shoot height and greater number of leaves than stems grown in an aquatic medium.
- Treatments subjected to direct sunlight produced a greater number of flowering shoots than those grown in shade.
- The influence of position of nodes on the stem in terms of inhibition or enhancement of shoot, root, flower or leaf production was not observed.
- Upper stem segments produced a greater percentage of flowering shoots than middle or lower segments, particularly when grown in full sun conditions.
- Stem segments taken from the middle section of mature plant stems achieved a greater success rate for shoot and root production than upper or lower segments.

- Lower stem segments produced taller shoots and a greater number of leaves at harvest than upper or middle segments indicating a relationship between nutrient reserves in stem material and subsequent growth potential.

The invasive potential of *F. japonica* stems is enhanced in an aquatic medium in terms of regeneration success and the speed at which regeneration occurs. However, when buried in a soil medium, stems produce not only shoots but are more likely to produce a root system which provides support for greater shoot height and a greater number of leaves. Once a root system is established, buried stems become more sustainable and are more likely to lead to the successful establishment of new plants. Management practice should therefore include consideration of the disposal of stem material following cutting or mowing.

The results of this study have shown that small fragments of rhizome are sufficient to produce new plants. The results obtained suggest that there is a minimum length requirement of 2 cm to obtain a 50 % regeneration rate and a minimum of 4 cm to achieve a rapid response time, above which rate of regeneration and success rates are not enhanced. Larger fragments (8 cm in this study) provide a greater resource for shoot elongation and leaf production but are no more successful in terms of regeneration. Management should therefore be geared towards preventing spread of all size fragments of rhizome material.

There is a need to develop comprehensive management strategies with integrated measures to prevent the spread of *F. japonica* through rhizome and stem tissue.

Future management of the plant will need to take account of the relationship between *F. japonica* and its related species and hybrids.

3.0 HYBRIDISATION IN THE *FALLOPIA* GENUS

3.1 INTRODUCTION

Fallopia japonica in its native range (Japan, Taiwan and northern China) exists as a functionally dioecious species (Ohwi, 1965), that is to say, male-fertile and male-sterile (female) flowers are produced on separate plants. In its native range, the main means of dispersal of *F. japonica* is by seed (Maruta, 1976; 1983; 1994). Male-fertile and male-sterile plants are reported in the introduced range of the plant, in Europe (Alberternst, 1995) and in the USA (Locandro, 1973; Seiger, 1993; 1997). However, in the British Isles, *F. japonica* exists only in its male-sterile (female) form (Bailey, 1989).

A number of species closely related to *F. japonica* also exist in the British Isles. Two of these, *F. sachalinensis* (giant knotweed) and *F. japonica* var. *compacta* have similar characteristics to *F. japonica*. All three species are stout, erect, rhizomatous perennials, have a vigorous growth habit and were introduced as ornamental plants from Asia in the late nineteenth century (Hooker, 1880a; 1880b; 1881). A fourth species, the twining woody shrub *F. baldschuanica* (Russian vine), again a rhizomatous perennial, was also introduced to the British Isles as an ornamental plant. In addition, *F.* x *bohemica,* a hybrid between *F. sachalinensis* and *F. japonica* has been recorded in the British Isles (Bailey and Conolly, 1984; Bailey, 1988; Bailey and Conolly, 1991; Bailey *et al.*, 1995; Bailey *et al.*, 1996). Sex expression in this group of species is complex and ranges through hermaphrodite (flowers with both fully functional male and female parts on the same plant) to fully dioecious (separate male and female plants) (Figure 3.5). In the British Isles, *F. japonica* exists only as female plants i.e. the population is totally male-sterile and no true *F. japonica* pollen is available.

It has been suggested by Bailey (1994) that all *F. japonica* plants in the British Isles may be clonal, possibly from a single introduction *via* Von Siebold's nursery garden in Leiden, The Netherlands. Clonal plants are genetically identical, with new individuals arising only by asexual reproduction. The high rate of vegetative regeneration of *F. japonica* from stem and rhizome fragments, as described in Chapter 2, combined with dispersal *via* natural and anthropogenic disturbance lends weight to this argument. So, it has generally been considered that for *F. japonica*, a single sex, possibly clonal population exists in the British Isles.

However, when *F. japonica* is examined in relation to the wider group of related species within the *Fallopia* taxon, the current situation in the British Isles becomes more complex. The first anomaly is that observations of *F. japonica* plants in the field have frequently reported seed set following flowering in late summer (Bailey, 1994). As all *F. japonica* plants in the British Isles are male-sterile, the availability of compatible pollen from another source is indicated. The second is the existence of the hybrid *F.* x *bohemica* in the British Isles, further suggesting a relationship between *F. japonica* and its congeners. It is also possible that male-fertile plants of the hybrid *F.* x *bohemica* could prove to be likely candidates for pollen availability.

The taxonomy of these species has been described in detail by a number of botanists. Early descriptions of this group of species (Lindley and Paxton, 1850-51) refer to the plants as belonging to the Order of Buckwheats (*Polygonaceae*), hence the previous nomenclature of *F. japonica* as *Polygonum cuspidatum* Siebold and Zuccarini syn. *P. sieboldi* de Vriess (Hooker, 1880a). The genus *Fallopia* contains annual and perennial, herbaceous and woody and climbing taxa which Meissner in 1826 classified as section *Tiniaria* of the genus *Polygonum*. Following splitting of the genera into two distinct groups, *Fallopia* and *Reynoutria*, the species were classified as genus *Reynoutria*, hence *Reynoutria japonica* Houtt. More recently, analysis of chromosomes by Bailey and Stace (1992) following hybridisation studies, suggested that this group of species should be classified as genus *Fallopia* to include four sections:

- *Fallopia* to include the annual climbers
- *Parogonum* to include the perennial climbers
- *Sarmentosae* to include the woody climbers e.g. *Fallopia baldschuanica* (Russian vine)
- *Reynoutria* to include the robust rhizomatous herbaceous perennials *Fallopia japonica* and *Fallopia sachalinensis* (see Table 3.1).

The nomenclature in current use is *Fallopia japonica* (Houtt.) Ronse Decraene.

Table 3.1 Taxonomy of *F. japonica* in current use (Ronse Decraene and Ackeroyd, 1988).

GENUS: *Fallopia*			
SECTION	SECTION	SECTION	SECTION
Fallopia	*Parogonum*	*Sarmentosae*	*Reynoutria*
annual climbers	perennial climbers	woody climbers	rhizomatous perennials
		e.g. *F. baldschuanica*	e.g. *F. japonica*
			F. sachalinensis
			and *F. japonica* var. *compacta*

In order to examine the relationships between these species more closely, a detailed description of each species is necessary, particularly in terms of plant morphology, sex expression and chromosome number.

F. sachalinensis is native to the island of Sakhalin, north of Japan, and extends its range into the Japanese islands of Honshu and Hokkaido particularly on the Japan Sea side of the islands and at higher altitudes on high mountains (Ohwi, 1965). This species was introduced to Europe in the late nineteenth century as an ornamental and fodder plant (Hooker, 1881; Conolly, 1977). *F. sachalinensis* is a large plant reaching a height in excess of 5 meters with bamboo-like stems and large heart shaped leaves which are rounded at the base and are approximately 20 - 30 cm long. The plant has greenish flowers carried on shorter, denser panicles than those of *F. japonica*. The current distribution of *F. sachalinensis* in the British Isles is shown in Figure 3.1. Morphological characteristics are summarised in Table 3.2.

A sub-species of *F. japonica*, *Fallopia japonica* var. *compacta,* is a more compact variety, usually only reaching 0.7 - 1.0 m tall. It has smaller, more rounded, darker leaves with slightly crinkled edges and can also be distinguished by its slightly reddish brown flowers and red tinged stems (Ohwi, 1965). Although *F. japonica* var. *compacta* is recorded throughout Japan as *Polygonum cuspidatum*, a check of Japanese herbarium material (Adachi, pers comm.) confirmed that it is this variety which occurs in Japan at high altitudes (above 2,400 m) where it is a primary coloniser of volcanic gravels (Maruta, 1976; 1983). *F. japonica* var. *compacta* was also introduced to the British Isles as an ornamental garden plant (Hooker, 1880b) and was much favoured by gardeners for its compact and less invasive nature (Anon, 1879).

Since their introduction, both *F. sachalinensis* and *F. japonica* var. *compacta* have become naturalised in the British Isles (Conolly, 1977) and occupy similar habitats to those of *F. japonica*. Neither species has, as yet, become as invasive as *F. japonica* and *F. japonica* var. *compacta* is the least widely distributed of the three outside parks and gardens (Bailey and Conolly, 1991).

Fallopia baldschuanica, a perennial twining woody vine with a substantial rhizome system is native to Central Asia. It was also introduced as an ornamental garden plant and is now an established garden escapee in widely scattered localities in the British Isles on hedges, in thickets and on cliffs (Figure 3.2). It is a rapidly growing creeper and has been described by Lousely and Kent (1981) as "rampant in hedgerows" in rural environments. The current distribution of *F. baldschuanica* in the British Isles is shown in Figure 3.2.

F. x *bohemica*, the hybrid between *F. sachalinensis* and *F. japonica*, was first described by Chrtek and Chtková (1983) in the Czech Republic in the spa of Beloves near the town of Náchod in north-eastern Bohemia. *F.* x *bohemica* is synonymous with the *Reynoutria* x *vivax* hybrid described by Schmitz and Strank in Germany in 1985. By 1989, Bailey had collected 20 records of *F.* x *bohemica* for the British Isles and by 1993 this had increased to 60 records. The distribution of *F.* x *bohemica* has been mapped elsewhere in the introduced range of *F. japonica*, throughout Europe for example in Germany (Alberternst, 1995) and France (Schnitzler and Muller, 1998) and most recently in Australia (Conolly, 1998). A hybrid between *Reynoutria sachalinensis* (syn. *F. sachalinensis*) and *Reynoutria japonica* var. *uzenensis* (a sub species of *F. japonica*) is also recorded in Japan in herbarium material in the Makino herbarium, Tokyo Metropolitan University (personal observation).

Fallopia sachalinensis

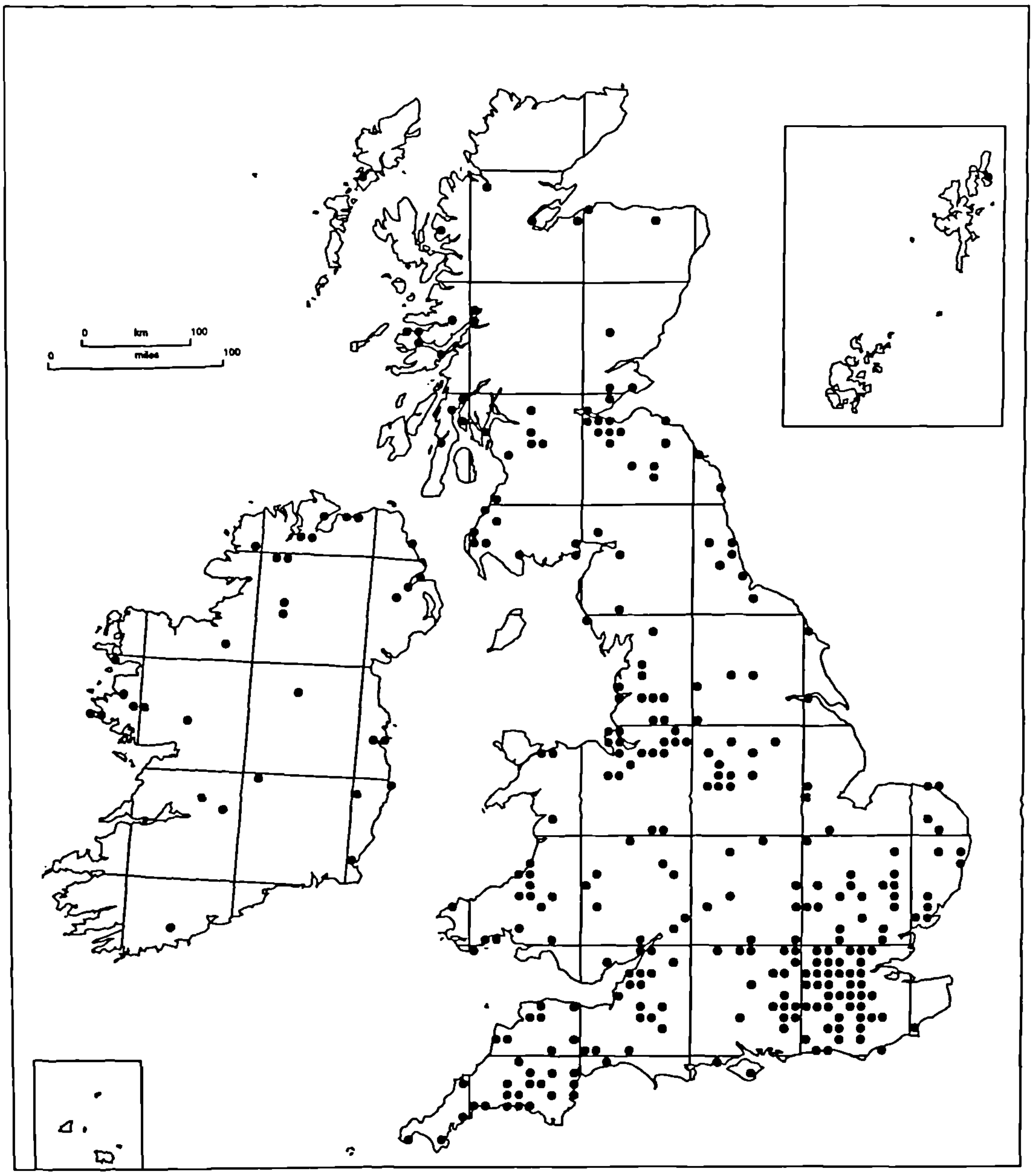


Figure 3.1 The current distribution of *F. sachalinensis* in the British Isles. Each dot represents at least one record in a 10km square of the National Grid. Mapped by the Biological Records Centre, Institute of Terrestrial Ecology, Monks Wood (1998).

Fallopia baldschuanica

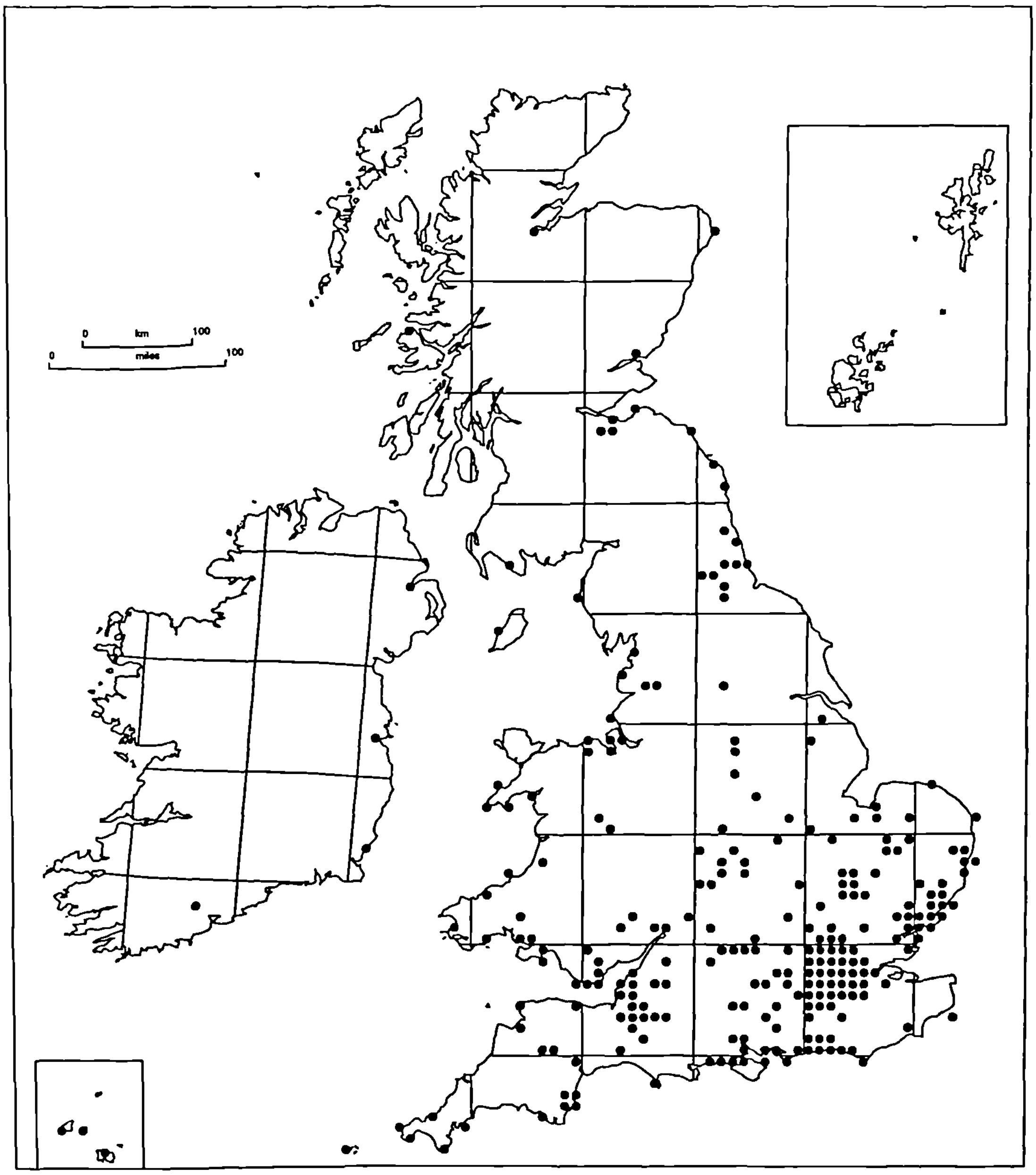


Figure 3.2 The current distribution of *F. baldschuanica* in the British Isles. Each dot represents at least one record in a 10km square of the National Grid. Mapped by the Biological Records Centre, Institute of Terrestrial Ecology, Monks Wood (1998).

F. x *bohemica* shows intermediate characteristics between *F. japonica* and *F. sachalinensis* in terms of growth habit, leaf shape and leaf size. The distinguishing morphological features of the parental plants *F. japonica* and *F. sachalinensis* and the hybrid *F.* x *bohemica* are shown in Table 3.2.

Table 3.2 Distinguishing features of *F. japonica*, *F. sachalinensis* and the hybrid *F.* x *bohemica*. (after Rich and Rich, 1988)

Species	***Fallopia sachalinensis*** (F. Schmidt ex Maxim.) Ronse Decraene Syn. *Reynoutria sachalinensis, Polygonum sachalinense*	***Fallopia japonica*** (Houtt.) Ronse Decraene Syn. *Reynoutria japonica, Polygonum cuspidatum*	***Fallopia* x *bohemica*** (Chrtek & Chrtková) J. Bailey (*F. sachalinensis* x *F. japonica* or *F. japonica* var. *compacta* x *F. japonica*)
Chromosome number	2n = 44	2n = 88	2n = 66, 44
Height	Striking, gigantic plant approx. 5m tall	Large plant up to 2-3m tall	Habit intermediate, 2.5-4m tall
***Leaf size/ character**	Basal leaves ovate to oblong, base cordate up to 400 x 220 mm in size	Leaves ovate, acuminate, base truncate 100-150 mm long	Leaves intermediate in size and shape, weakly to moderately cordate at base, tip acuminate up to 230 x190 mm in size
	Undersides of leaves with scattered, long, flexuous hairs (trichomes)	Undersides of leaves entirely glabrous	Undersides of larger leaves with numerous short, stout hairs (trichomes), (easily visible with a hand lens)
Floral biology	Male-fertile flowers (with exserted anthers) and male-sterile flowers (with small, empty included anthers and well developed stigmas) borne on separate plants	Flowers usually male-sterile	Male-fertile and male-sterile flowers borne on separate plants

* With these morphological characters it is important that only fully mature main stem leaves are used as differences are not so clearcut in young leaves or those from upper stems.

The hybrid, *F.* x *bohemica* can be distinguished from its parents on the basis of leaf shape, size and structure (Figure 3.3) although these features are not always easy to determine. Leaf structure is characterised by the presence of trichomes or hairs on the underside of leaves (Figure 3.4). Long flexous hairs up to 5 mm long can be seen along veins on the underside of leaves of *F. sachalinensis* quite easily with the naked eye. These hairs are not present on *F. japonica* leaves which are smooth or glabrous on the undersides. *F.* x *bohemica* leaves have trichome hairs of approximately 1 mm - 2 mm long which are clearly visible with a hand lens. There is some variation in length of trichomes in hybrid material but they are generally more stout than those seen in *F. sachalinensis.*

Sex expression can also be used as an indicator of hybrid plants. Male-fertile flowers have exserted stamens with full anthers whereas male-sterile (female) flowers have small included stamens with empty anthers (Figure 3.5). Male-fertile plants which are obviously not either *F. sachalinensis* or *F. japonica* have so far been found to be hybrids (Bailey *et al.*, 1996).

In order to investigate these related species as potential sources of pollen, it is necessary to explore their sex expression. *F. sachalinensis* exists in the British Isles as both hermaphrodite and male-sterile (female) plants, a pattern of sex expression known as gynodioecy (Bailey, 1990). *F. japonica* var. *compacta* plants examined by Bailey have been found to be either male-fertile or male-sterile (female) although seed has occasionally been noted on male-fertile plants leading Bailey to propose a classification of sub-dioecious (Bailey 1994). Clearly the pattern of sex expression in this group of species is complex. What is certain however, is that *F. japonica* exists only as male-sterile (female) plants in the British Isles and that male-fertile *F. sachalinensis*, *F. japonica* var. *compacta* and *F. baldschuanica* could all potentially be candidates for provision of pollen providing they are found to be compatible with *F. japonica.*

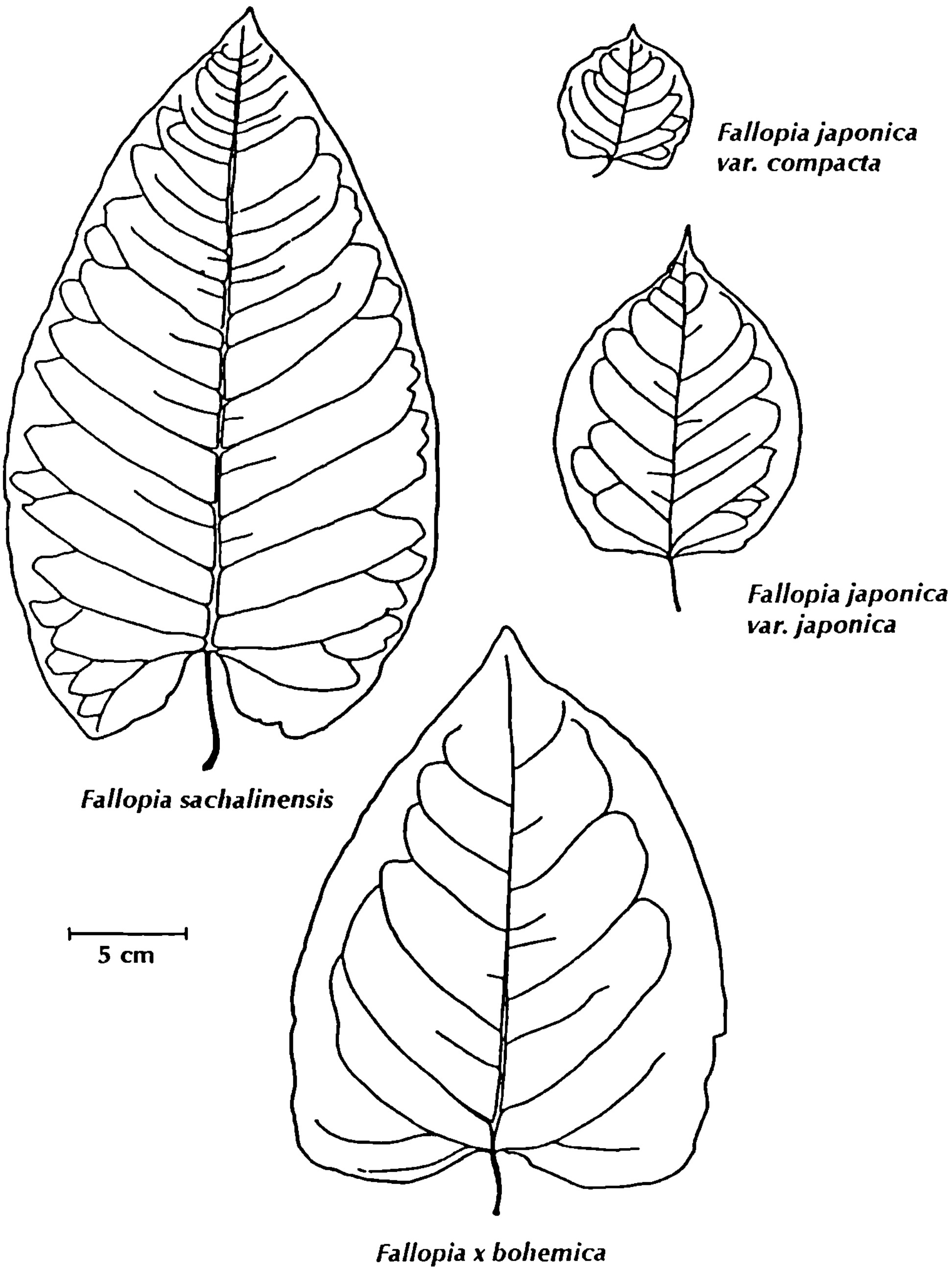


Figure 3.3 Typical leaf characteristics (shape and relative size) of *F. japonica*, *F. sachalinensis*, *F. japonica* var. *compacta*, and *F.* x *bohemica.*

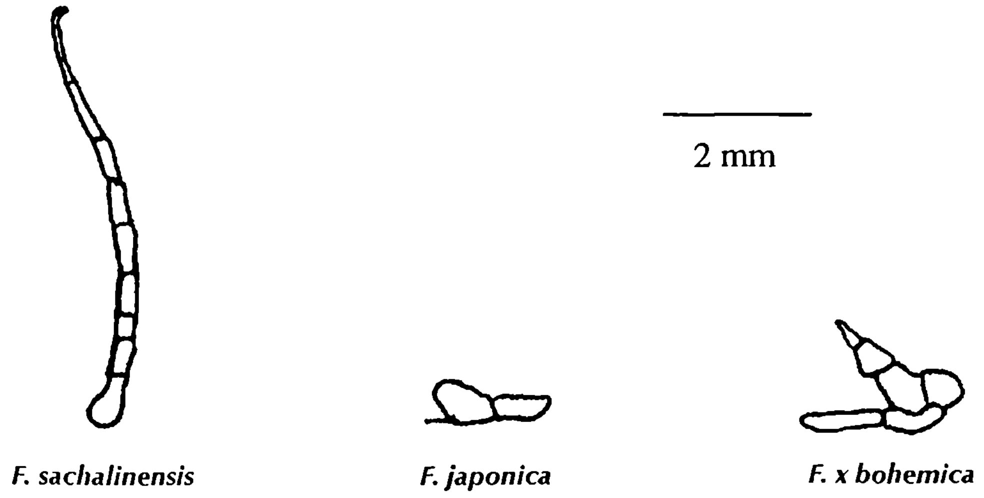
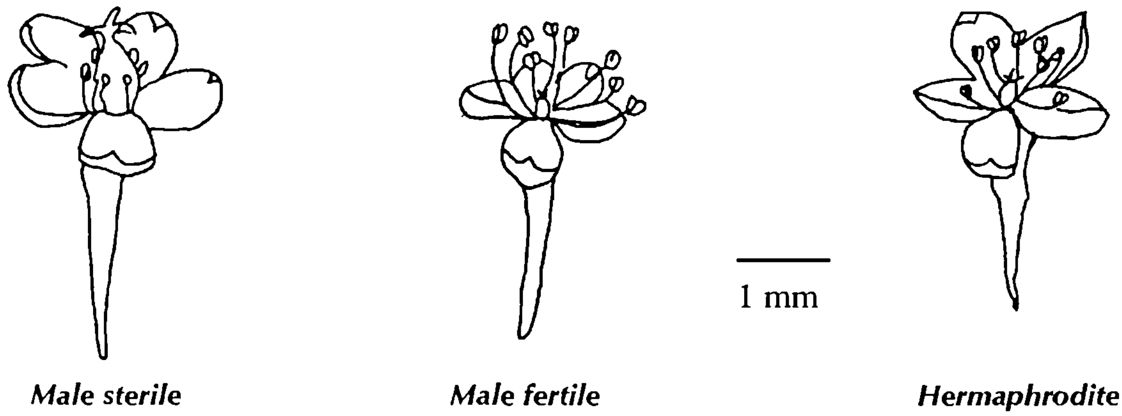


Figure 3.4 Characteristics of trichomes (hairs) on the underside of leaves of *F. japonica*, *F. sachalinensis* and *F.* x *bohemica*.



Found on:	Found on:	Found on:
F. japonica in all cases *F. sachalinensis* *F.* x *bohemica* *F. japonica* var. *compacta*	*F. sachalinensis* *F.* x *bohemica* *F. japonica* var. *compacta*	*F. sachalinensis* *F.* x *bohemica* *F. japonica* var. *compacta* *F. baldschuanica*

Figure 3.5 Flower characteristics of *F. japonica* and its congeners in the British Isles

There are three main factors to consider in an investigation of compatibility:

1. co-incidence of flowering period
2. pollen viability
3. compatibility of chromosome number

Co-incidence of flowering is necessary to ensure that pollen is produced at the same time as female flowers are produced. In the British Isles, the flowering period of the three candidate species (*F. sachalinensis*, *F. japonica* var. *compacta* and *F. baldschuanica*) co-incides with that of *F. japonica*. Flowers are produced by each of these species during late summer, generally from early August through to October.

Pollen produced must be viable in order that successful fertilisation can take place. The viability of pollen produced by *F. sachalinensis* and *F. japonica* var. *compacta* has been studied by Bailey (1994) in *in-vitro* experiments. *F. japonica* var. *compacta* and *F. sachalinensis* pollen gave mean percentage germination rates of 36.1 and 22.1 percent respectively indicating viable pollen from these sources. Pollen-stigma interactions have confirmed that fertile pollen is produced by these species and that the stigmas of *F. japonica* plants are compatible with the pollen produced by both species (Bailey, 1994).

Regular meiosis requires that complete pairing of chromosomes occurs during the formation of gametes (irregular meiosis leads to low fertility). Chromosome counts are assessed from freshly prepared plant material, where cell nuclei are stained and chromosomes are counted under high power magnification. Chromosome compatibility at fertilisation was found for *F. japonica* when artificially fertilised by both *F. sachalinensis* and *F. japonica* var. *compacta*.

F. japonica, *F. sachalinensis* and *F. japonica* var. *compacta* all exhibit some level of polyploidy with a base chromosome number of 11. Polyploidy relates to the number of multiples of chromosomes found in the cell nucleus. *F. japonica* in the British Isles exists in its octoploid form (2n = 88) although *F. japonica* from Japanese specimens has been found to be tetraploid (2n = 44). *F. sachalinensis* and *F. japonica* var. *compacta* are tetraploid (2n = 44) in both their native and introduced ranges. *F. baldschuanica* has a base chromosome number of 10 and exists only in its diploid form (2n = 20). The hybrid *F.* x *bohemica* exists in two forms, a hexaploid (2n =

66), dependent on the female parent being *F. japonica* (2n = 88) and a tetraploid (2n = 44) with the female parent as *F. japonica* var. *compacta* or *F. sachalinensis* (2n = 44) (Table 3.3). The two forms of *F.* x *bohemica* are not always distinguishable purely by morphological features. The great majority of British hybrid plants can be attributed to the hybrid constitution *F.* x *bohemica* (2n = 66) (*F. japonica* (2n = 88) x *F. sachalinensis* (2n = 44)) (Bailey and Conolly, 1985).

During investigations of hybridisation (Bailey, 1989), a collection of artificial hybrids was created and viable seed was obtained from hybrids of constitution:

F. japonica x *F. sachalinensis*
F. japonica x *F. japonica* var. *compacta* and
F. sachalinensis x *F. japonica* var. *compacta.*

The collection was grown to maturity and cytological examination of the various hybrids was undertaken. This has provided reference cytological evidence against which wild plant material can be compared. Availability of pollen from *F. sachalinensis* and *F. japonica* var. *compacta* is possibly limited due to the relatively sparse distribution of these species in relation to *F. japonica* (Figures 1.7 and 3.1). However, observations of seed set on *F. japonica* plants throughout the British Isles indicated that a widespread source of pollen must be available. Following cytological examination of seed material, this source was established as being *F. baldschuanica* (Russian vine) (Bailey and Conolly, 1991; Bailey and Stace, 1992). This unexpected hybridisation route led to the reclassification of this group of species (previously classified as *Polygonum* and subsequently *Reynoutria*) from the genus *Reynoutria* to the genus *Fallopia* section *Reynoutria* (Ronse Decraene and Ackeroyd, 1988) (Table 3.1). The majority of seed observed in the British Isles on *F. japonica* plants to date has been determined as having the constitution *F. japonica* x *F. baldschuanica* (2n = 54) (Bailey, 1994). However, only one live plant of this constitution has been recorded in Britain, at railway sidings in Haringey, north London (Bailey 1992). Seiger (1997) confirmed that seed set in the USA is also the product of hybridisation, with *F. baldschuanica* the major provider of pollen.

Given that *F. japonica* has been shown to be compatible with the related species *F. sachalinensis*, *F. japonica* var. *compacta* and *F. baldschuanica*, Table 3.3 explores the various hybridisation routes which are theoretically possible and gives an indication of occurrence, where known, of these hybrids in the wild.

Table 3.3 Possible hybridisation routes within this group of *Fallopia* species.

FEMALE PARENT		MALE PARENT		HYBRID	OCCURRENCE
F. japonica (2n = 88)	x	*F. sachalinensis* (2n = 44)	→	*F.* x *bohemica* (2n = 66)	Hybrid plants recorded in the wild throughout Europe
F. japonica (2n = 88)	x	*F. japonica* var. *compacta* (2n = 44)	→	*F.* x *bohemica* (2n = 66)	Recorded as an artificial hybrid - only one plant recorded in the wild (Bailey and Conolly, 1991)
F. sachalinensis (2n = 44)	x	*F. japonica* var. *compacta* (2n = 44)	→	*F.* x *bohemica* (2n = 44)	Hybrid plants recorded in the wild throughout Europe
F. japonica var. *compacta* (2n = 44)	x	*F. sachalinensis* (2n = 44)	→	*F.* x *bohemica* (2n = 44)	Hybrid plants recorded in the wild throughout Europe
F. japonica (2n = 88)	x	*F baldschuanica* (2n = 20)	→	Hybrid (2n = 54)	Recorded as seed throughout the British Isles - only one plant recorded in the wild (Bailey, 1992)
F. sachalinensis (2n = 44)	x	*F. baldschuanica* (2n = 20)	→	Hybrid (2n = 32)	Recorded as seed throughout the British Isles plus artificial hybrid
F. japonica var. *compacta* (2n = 44)	x	*F. baldschuanica* (2n = 20)	→	Hybrid (2n = 32)	Recorded as an artificial hybrid only

Clearly, the genetic relationship within this group of *Fallopia* species is complex. *F. japonica* is polyploid and is only found in its male-sterile (female) form in the British Isles. However, seed set is observed frequently throughout the British Isles, the majority observed to date having been found to be the result of hybridisation between

F. japonica and *F. baldschuanica*. Hybrid plants also exist in the British Isles, the majority being hybrids between *F. japonica* and *F. sachalinensis*. Theoretically, a number of other hybrid forms may exist (Table 3.3).

3.1.1 Aims and objectives of this study

The aim of this study was to understand the implications of the complexity of the genetics of the *Fallopia* taxon in relation to future management of this group of species. Taking the most widely distributed of the hybrids, *F.* x *bohemica*, a study was initiated to determine some characteristics of this population. Prior to this study, *F.* x *bohemica* hybrid plants had been recorded in the wild throughout the British Isles on an *ad hoc* basis and it was not clear whether these records represented a complete record of distribution. Records have been collected by interested botanists and have been included in some County Floras (e.g. Wade *et al.*, 1994) but these gave little indication of the extent of the hybrid distribution or of the types of habitats in which the plant was found. In addition, little information has yet been collected on the proportion of male-fertile plants within hybrid populations. The availability of a source of pollen from male-fertile hybrid plants could result in successful sexual reproduction, with the possibility of future dispersal of this group of species *via* seed. The existence of hybrid plants bearing male-fertile flowers would therefore be of interest to future management of this group of species.

More specifically, the objectives of this study were to:

- improve knowledge of the current extent of the distribution of the hybrid in the British Isles
- create a database from which the rate of spread of *F.* x *bohemica* could be observed in the future
- assess the proportion of male-fertile plants within hybrid populations
- assess the genetic constitution of hybrid plants at sample locations
- compare habitat types for hybrid plants with those of *F. japonica*
- assess whether the distribution of the hybrid should be a cause for concern to environmental managers

3.2 METHODS

A survey of hybrid distribution was undertaken to assess whether distribution was indeed limited to the 60 locations (Bailey, pers. comm.) identified prior to 1993. A ground survey of the whole of the British Isles was not practicable in this study therefore the expertise of a number of botanical organisations was called upon. Members of the Botanical Society of the British Isles (BSBI), subscribers to the Arboricultural Information and Advisory Service (AIAS) and members of the Henry Doubleday Research Association (HDRA) were invited to participate in the study through their regular newsletters. A specially constructed survey form which requested assistance was included in each of the newsletters. Surveys commenced in the autumn of 1993 and continued for three growing seasons. The survey form gave details of the identification of the parent plants and the hybrid, requesting information on location, habitat, and area of ground covered by hybrid plants. A copy of the recording sheet is shown in Appendix 1. In addition to the written information, a sample leaf was requested in order to allow verification of plant type by morphological methods, e.g. leaf shape, leaf size and the presence or absence of trichome hairs on the underside of the leaf. Leaves were catalogued on herbarium sheets and were checked for validity by John Bailey and Ann Conolly at Leicester University. Flower samples sent in addition to leaves were used to determine the sex of plants.

Hybrid records were compiled as a list of hybrid locations which were then assembled by the Biological Records Centre at Monks Wood as a distribution map.

In order to gain a better understanding of the extent of hybridisation at particular sites, a field study was carried out. Two sites were selected where hybrids had been recorded in proximity to both *F. sachalinensis* and *F. japonica* plants. One site was adjacent to the A429 to the north of Cirencester, (National Grid reference SP 039033) on a roadside verge, and the other in the grounds of Cirencester Abbey (National Grid reference SP 025023). Patch size (area covered by plants) was measured, samples of leaf and flower material were collected and samples of rhizome were collected for later chromosome counts at Leicester University. A 1 km stretch of the A429 was surveyed, with locations of *Fallopia* plants mapped at a scale of 1:25,000. A detailed study of the Abbey Gardens was made, again recording individual plants and recording site details.

3.3 RESULTS

3.3.1 Results of the postal survey

Of 4,700 recording sheets circulated, over 300 replies were received, the majority of these from BSBI and HDRA members. As there was no obligation to participate in the survey a large response was not expected. The vice counties (a unit used by botanists for organising the recording of plant species) from which responses were received are shown in Figure 3.6. Coverage of England and Wales was achieved with areas well represented in the south and west of England. No responses were received from East Anglia or from the eastern counties north of the Humber estuary. Scotland was represented by several responses from the west and central highlands. No respondents sent in records for sites already recorded and only one location was duplicated in the survey. This was an extensive patch at Cannonhill Park, Edgbaston which was recorded by three respondents.

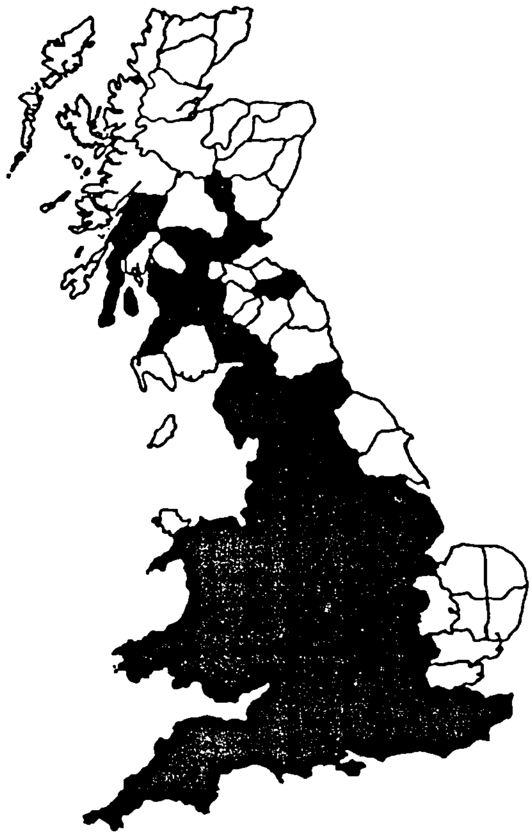


Figure 3.6 Distribution of responses received as a result of the postal survey. Shaded areas mark vice counties from which responses were received.

The majority (80%) of survey returns were for *F. japonica*. Figure 3.7 shows the percentage of survey responses which were correctly identified by respondents. The majority of responses correctly identified the various forms of *Fallopia* species. Correct identification was greatest for *F. japonica* (88%) and lowest for *F. sachalinensis* (48%). The hybrid, *F.* x *bohemica* was correctly identified in 69% of responses. The most common mistake on survey responses was to mis-identify *F. sachalinensis* as *F.* x *bohemica* (52%)

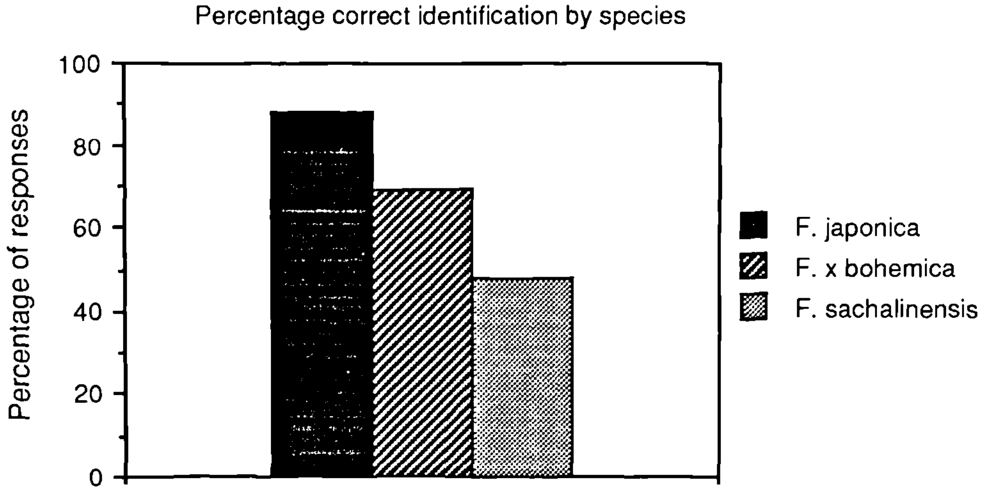


Figure 3.7 Percentage of responses from postal surveys with correct identification for *Fallopia* species.

Figure 3.8 shows the predominant habitats where *F. japonica*, *F.* x *bohemica* and *F. sachalinensis* were recorded. All three species were recorded in similar abundance along road verges, however *F.* x *bohemica* was also observed along river or stream corridors but percentages were much lower than those for *F. japonica*. No records of the hybrids were received for rail corridors although two records were received for *F.* x *bohemica* at railway stations (Charlton and Maze in Greater London). Thirty percent of records for the hybrid were for gardens which was a considerably higher percentage than that recorded for either *F. japonica* or *F. sachalinensis*. Other habitats where *F.* x *bohemica* was recorded included sea shore, woodland and field boundaries. *F. sachalinensis* and *F. japonica* were also recorded in urban areas such as car parks.

The area covered by the hybrid plants at each location ranged from 2 m^2 to 300 m^2, values comparable with patch sizes for *F. japonica* which ranged from 2 m^2 to 500 m^2. Both species can occupy extensive areas at sites where they are present.

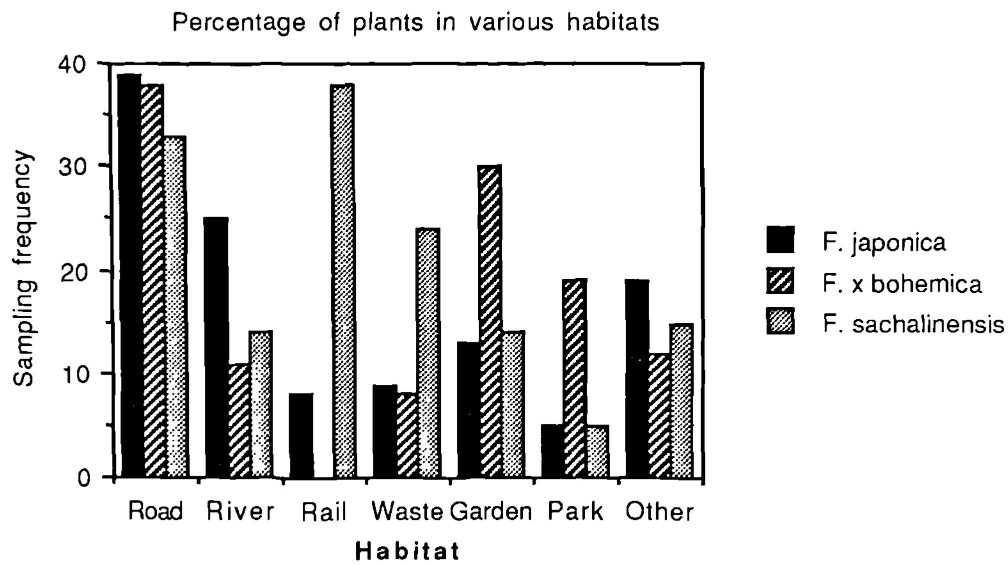


Figure 3.8 Percentage of the various *Fallopia* species recorded in the survey by habitat. (Data are from survey responses)

Figure 3.9 shows the distribution of *F.* x *bohemica* plants recorded as presence or absence in 10 km squares. Open circles represent those records which had been collected prior to the survey from County Flora Committees and by Leicester University. Closed circles represent at least one location of *F.* x *bohemica* in a 10 km square recorded during this survey. A large number of records were collected by a single recorder in Surrey and circles therefore represent a number of records within the locality.

Table 3.4 lists the hybrid records by vice county. New hybrid records are denoted with an asterisk. In total 71 new records were added to the database. Where available, sex expression of plants was recorded, determined by flower type. Chromosome numbers, where determined, are included.

Fallopia x bohemica

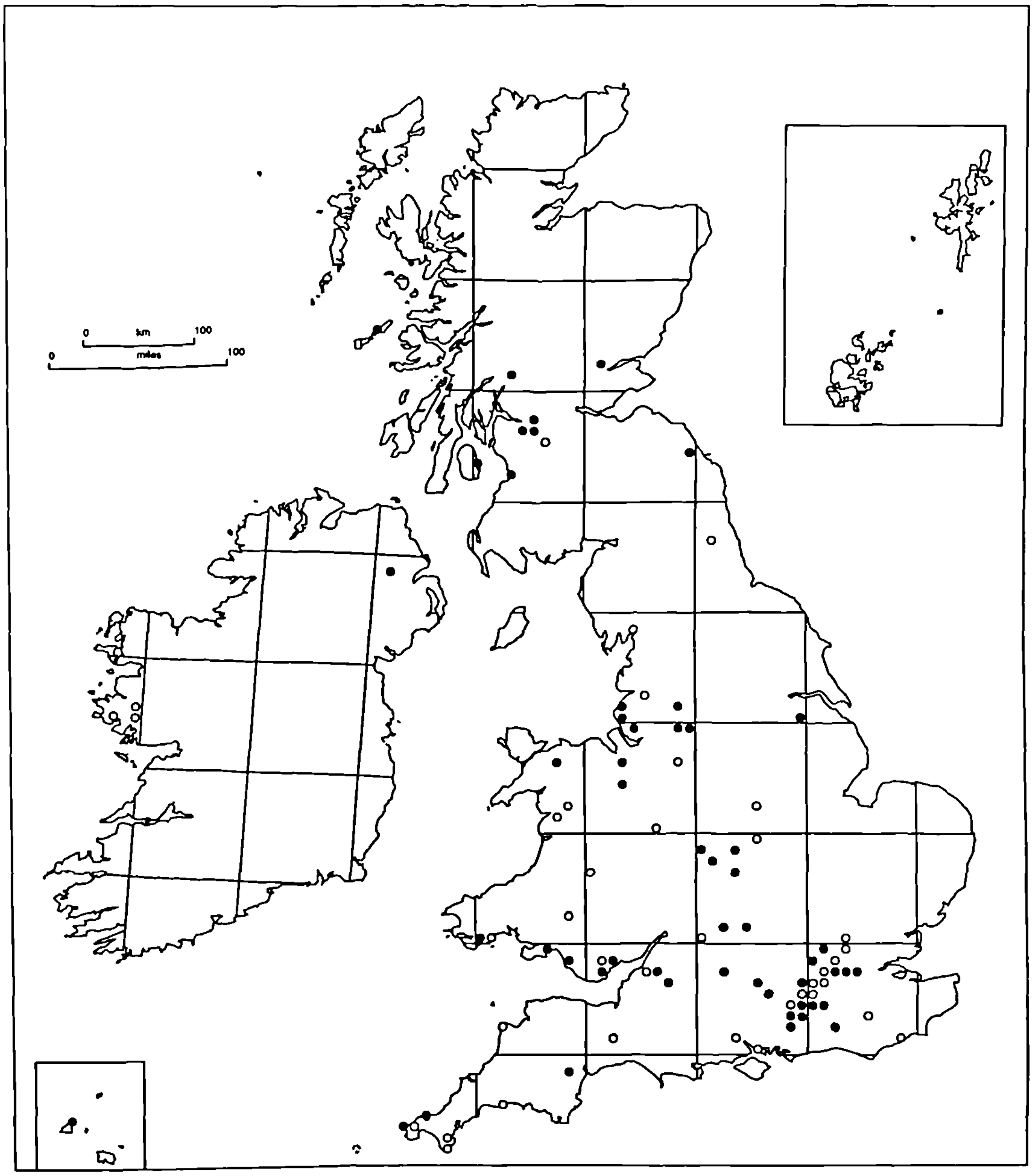


Figure 3.9 Distribution of *F.* x *bohemica* in the British Isles from survey records. (Biological Records Centre, Institute of Terrestrial Ecology, Monks Wood, 1998) Each dot represents at least one record in a 10 km square of the National Grid. Open circles show records prior to 1993, closed circles represent records collated during this survey.

Table 3.4 Occurrence of the hybrid *F.* x *bohemica* in the British Isles listed by locality, vice county and National Grid reference.
* denotes a new hybrid record from the BSBI, AIAS and HDRA surveys.

LOCALITY	VICE COUNTY	GRID REFERENCE	SEX EXPRESSION	CHROMOSOME NUMBER
England, Wales and Scotland				
Towednack, W. Cornwall	v.c.1	SW 43 38		2n = 66
Lanarth, W. Cornwall	v.c.1	SW 770 210	male-fertile	
*St Ives, Cornwall	v.c.1	SW 518 403		
*St Just, Cornwall	v.c.1	SW 361 313		
*Coverack, Cornwall	v.c.1	SW 781 185		
Polperro, E. Cornwall	v.c.2	SX 226 516	male-fertile	2n = 66
*Trenchford reservoir	v.c.3	SX 804 824		
*Philham, N. Devon	v.c.4	SS 259 234		
Otterford Lakes, S. Somerset	v.c.5	ST 224 138		
*Freshford, Bradford on Avon	v.c.6	ST 784 600	male-fertile	
Rownham, N. Somerset	v.c.6	ST 56 72		
Belmont Hill, SW of Bristol	v.c.6	ST 517 704		
*Aldbourne	v.c.7	SU 271 753		
*Aldbourne	v.c.7	SU 262 756		
*Aldbourne	v.c.7	SU 253 773		
Sarisbury, S. Hants.	v.c.11	SU 500 079		
Southhampton	v.c.11	SU 395 141		
*Hartley Wespall	v.c.12	SU 696 575	male-fertile	
*Basingstoke, A33	v.c.12	SU 677 569		
*Ashfold, W. Sussex	v.c.13	TQ 239 286		
*Midhurst	v.c.13	SU 872 208	male-fertile	
*Fernhurst, W. Sussex	v.c.13	SU 880 267		
Lye Green, E. Sussex.	v.c.14	TQ 511 336	male-fertile	2n = c. 66
*Coghurst Wood, Guestling	v.c.14	TQ 830 134	male-fertile	
Honor Oak Cemetery, W. Kent	v.c.16	TQ 354 744	male-fertile	2n = 66
*Maze Hill railway station	v.c.16	TQ 392 778		
*Charlton railway station	v.c.16	TQ 419 782		
*Gomshall, Surrey	v.c.17	TQ 087 478	male-sterile	2n = 44
Haslemere, roadside	v.c.17	SU 891 332		
*Critchmere Nr. Frensham Hall Farm	v.c.17	SU 882 334		
*Critchmere, A289	v.c.17	SU 882 337	male-fertile	
*Nutcombe	v.c.17	SU 884 432	male-fertile	
*Shottenmill Polecat Copse	v.c.17	SU 886 340	male-fertile	
*Shottenmill, Stoatley Green	v.c.17	SU 895 339	male-fertile	
*Shottenmill, Lower Hanger, Wolmer Hill	v.c.17	SU 877 330	male-sterile	
*Farnham	v.c.17	SU 856 454		
*Witley, Barrow Hills	v.c.17	SU 940 398	male-fertile	

LOCALITY	VICE COUNTY	GRID REFERENCE	SEX EXPRESSION	CHROMOSOME NUMBER
*Witley, Barrow Hills School	v.c.17	SU 941 399	male-fertile	
*Witley , Culmer Hanger	v.c.17	SU 943 391		
*Guildford, Stringers Common	v.c.17	SU 993 526		
*Guildford, River Wey	v.c.17	SU 995 487	male-fertile	
*Guildford, Mead House	v.c.17	SU 995 488	male-fertile	
*Guildford, Wey Navigation	v.c.17	SU 998 511	male-fertile	
*Broadford, Shalford Common	v.c.17	SU 999 471	male-fertile	2n = 44
*Guildford, Sutton Green	v.c.17	TQ 000 541		
*Guildford	v.c.17	TQ 003 509		
*Farley Green	v.c.17	TQ 058 454		
*Albury Heath	v.c.17	TQ 061 465		2n = 66
*Abinger Hammer, B2126	v.c.17	TQ 097 464	male-fertile	
*Holmbury Hill	v.c.17	TQ 099 430	male-sterile	2n = 66
*Holmbury St. Mary	v.c.17	TQ 105 427	male-sterile	2n = 66
*Wonersh	v.c.17	TQ 034 446		
Wisley, RHS Gardens	v.c.17	TQ 066 584	male-sterile	
*Weybridge,	v.c.17	TQ 067 641		
*Holmbury St. Mary, Cricket ground	v.c.17	TQ 109 439		
*Holmbury St. Mary	v.c.17	TQ 112 444		
*Esher, river bank	v.c.17	TQ 112 627		
*Burhill golf course	v.c.17	TQ 104 627		
*West Molesey	v.c.17	TQ 132 668		
Ham riverlands	v.c.17	TQ 165 721	male-sterile	
Cheshunt, Herts.	v.c.20	TL 368 028	male-sterile	2n = 44
*Northwood, A4125	v.c.20	TQ 100 929	male-fertile	
*Buckingham Palace Gardens	v.c.21	TQ 287 795	male-fertile	2n = 66
Tottenham Marshes, Middlesex	v.c.21	TL 352 909	male-sterile	2n = 44
Regents Park, Middlesex	v.c.21	TQ 286 826		
*Woolhampton, near Newbury	v.c.22	SU 566 682		
*Shipton under Wychwood, A361	v.c.23	SP 273 176	male-fertile	
*Blenheim Park, Woodstock	v.c.23	SP 43 15	male-fertile	
*Black Park Country Park, Wexham	v.c.24	TQ 014 832		
Cirencester, Abbey Grounds	v.c.33	SP 025 023	male-sterile	2n = 66
Cirencester, Abbey Grounds	v.c.33	SP 025 023	male-fertile	2n = 66
Cirencester, Abbey Grounds	v.c.33	SP 025 023	male-sterile	2n = 44
Cirencester A429	v.c.33	SP 039 033	male-sterile	2n = 44
*Cirencester A429	v.c.33	SP 039 033	male-sterile	2n = c.66
Bristol, old dockside railway	v.c.34	ST 57 72	male-fertile	
Bristol, east of suspension bridge	v.c.34	ST 565 728	male-sterile	
Bristol	v.c.34	ST 531 777	male-sterile	2n = 66
* River Frome, Frenchay, Bristol	v.c.34	ST 641 772	male-fertile	
Newport	v.c.35	ST 290 853	male-fertile	
Newport	v.c.35	ST 291 854	male-fertile	
*Edgbaston, Cannon Hill Park	v.c.38	SP 066 841	male-fertile	
*Edgbaston, Cannon Hill Park	v.c.38	SP 068 826		
*Corley B4098	v.c.38	SP 304 845		
*Leamington Spa, Mid Warks. College	v.c.38	SP 308 656		
*Cheswick Green A34/M42 intersection	v.c.38	SP 145 757	male-fertile	
Ironbridge	v.c.40	SJ 67.03	male-sterile	2n = 66
Whitchurch, Velindre Lodge	v.c.41	ST144 802	male-fertile	2n = 66

LOCALITY	VICE COUNTY	GRID REFERENCE	SEX EXPRESSION	CHROMOSOME NUMBER
Whitchurch, golf club	v.c.41	ST 154 818		
Ogmore, Merthyr Mawr	v.c.41	SS/87 87	male-sterile	
Roath	v.c.41	ST 1 7	male-fertile	
Swansea, Blackpill, ornate bridge	v.c.41	SS 619 907	male-fertile	
Swansea, Blackpill, rear of car park	v.c.41	SS 619 908	male-fertile	
Swansea, Blackpill, DerwenFawr Road	v.c.41	SS 617 908	male-fertile	
Llandridnod Wells	v.c.43	SO 058 612	male-fertile	2n = 66
Amroth	v.c.45	SN 167 071	male-fertile	2n = 66
*Glamorgan, south west of A465	v.c.45	SN 008 036		
Pont Rhyd Sarn, Llanuwchllyn	v.c.48	SH 859 287	male-fertile	2n = c. 66
Brithdir, Caerynwch Hall	v.c.48	SH 763 177	male-fertile	2n = 66
Dolgellau, Towyn Road	v.c.48	SH 711 183	male-sterile	2n = 66
Dolgellau, riverside	v.c.48	SH 723 180	male-fertile	
Llyn Crafnant, Trefriw	v.c.49	SH 753 626		
Dee embankment	v.c.51	SJ 360 664		
Clywedog Valley, Kings Mills	v.c.50	SJ 341 489	male-fertile	
*Mortal Ash Hill, off A18, Scunthorpe	v.c.54	SE 963 071		
Blaby, Leicester	v.c.55	SP 577 977		
Loughborough	v.c.55	SK 544 204	male-fertile	2n = 66
Small Wood End, near Sandbach	v.c.58	SJ 806 602		2n = 66
*River Goyt nr. Stockport	v.c.58	SJ 917 907		
*River Goyt nr. Stockport	v.c.58	SJ 918 906		
Ainsdale	v.c.59	SD 307 119		
*Southport, Victoria Park	v.c.59	SD 326 166		
Southport,	v.c.59	SD 332 178	male-fertile	2n = 66
Southport	v.c.59	SJ 407 905		
Ince, Blackwall Lane	v.c.59	SD 330 022		
Liverpool, railway near Broad Green	v.c.59	SJ 407 905		
Heaton,Mersey	v.c.59	SJ 886 901		
Preston, A583	v.c.60	SD 510 298	male-fertile	2n = c. 66
South Wylam, east of railway station	v.c.66	NZ124 646	male-fertile	2n =44
Ayr	v.c.75	NS 33 21		2n = 66
*Johnstone, Quarrelton	v.c.76	NS 414 625	male-fertile	
*Near. Bothwell, Lanarks.	v.c.77	NS 69 59		
*Glasgow, River Kelvin	v.c.77	NS 568 680		
*Dumbrock Loch	v.c.86	NS 547 782	male-fertile	
Near Inverarnan Bridge	v.c.87	NN 319 186		
*Scone Palace Grounds	v.c.89	NO 118 263		
*Brodick Country Park I. of Arran	v.c.100	NS 014 376		
Channel Islands				
*Chateau des Marais Guernsey	v.c.113	WV 333 803		
Ireland				
Recess	v.c.H16	L90 46		2n = 66
Maam, W. Galway.	v.c.H16	L 963 533	male-sterile	2n = 66
Roundstone, W. Galway	v.c.H16	L 726.424		2n = 66
Lough Neagh, Antrim	v.c.H40	J 13 86		

A total of 131 hybrid records now exist for the British Isles. This translates into 81 of the 10 km squares used to map plant distribution. The number of male-fertile hybrids identified in the British Isles prior to survey was 23. This survey has added a further 23 records of male-fertile hybrid plants. A summary of determination of sex and chromosome number is shown in Table 3.5.

Table 3.5 Summary of *F.* x *bohemica* survey results. Data presented are raw numbers. Figures in italics (shown in brackets) are percentages of total record numbers.

	PRIOR TO SURVEY		DURING SURVEY		TOTAL
Number of records	60	*(45%)*	71	*(54%)*	131
Male-fertile plants	23	*(50%)*	23	*(50%)*	46
Male-sterile plants	13	*(76%)*	4	*(23%)*	17
Hexaploid plants (2n = 66)	21	*(80%)*	5	*(19%)*	26
Tetraploid plants (2n = 44)	5	*(71%)*	2	*(28%)*	7

A greater number of records were received from Surrey, (v.c. 17) than for any other vice county. This is in part due to the recording efforts of a dedicated botanist who systematically surveyed the county. A total of 33 records of hybrid plants were recorded which translate into ten 10 km squares on the distribution map. This scale of mapping gives only an overall view of the distribution of the plants in the area. In order to attempt to discern patterns of distribution, a larger scale than a 10 km grid is required. The Surrey records, when plotted on a 1 km grid square scale show an uneven distribution of the plants within 10 km squares (Figure 3.10). Groupings of hybrid plants can be seen around Shottenmill and Critchmere with both male and female plants present (SU 8833) and a band of hybrid locations along the River Wey in Guildford (TQ 0050). In order to determine accurate and comprehensive assessments of plant distribution, there is a need for more detailed survey techniques. These could include the use of, for example, Geographical Information Systems (GIS).

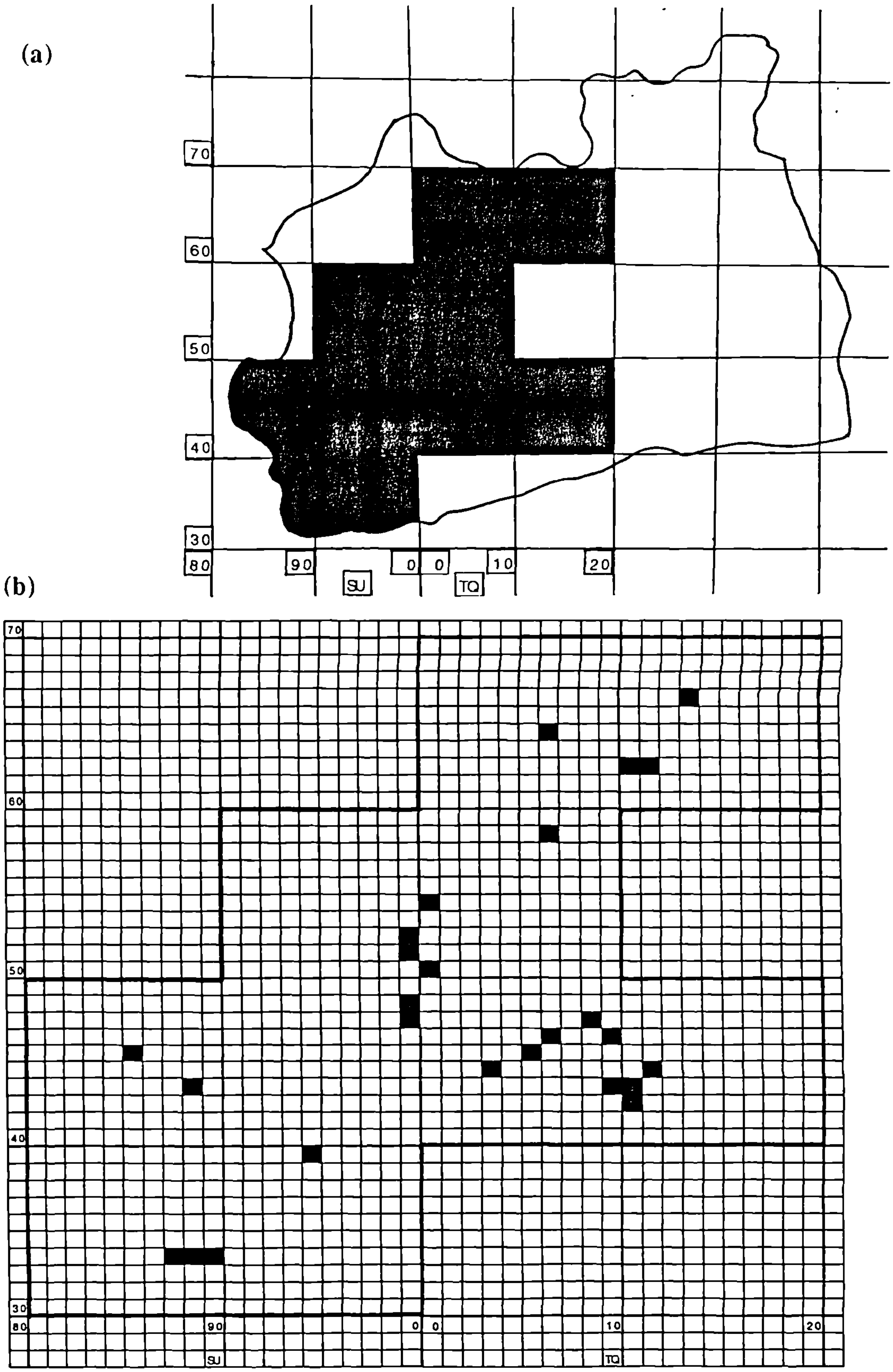


Figure 3.10 Distribution of hybrid records in Surrey (v.c. 17) plotted at (a) 10 km grid square scale and (b) 1km grid square scale.

3.3.2 Results of the Cirencester study

A total of 12 patches (area covered by *F.* x *bohemica* plants) were identified along the 1 km of A429 road verge surveyed (Figure 3.11, Table 3.6). Areas of patches ranged from 20 to 150 m^2. Total area covered was 688 m^2. All plants were positively identified as male-sterile *F.* x *bohemica* by morphological features. This was confirmed by chromosome analysis, all but one of the patches being hexaploid (2n = 66). The remaining patch (patch 9) was tetraploid (2n = 44) (Table 3.6). Plants in the majority of patches were 1.5 - 2.0 m in height although some mowing had been carried out close to the road and in these areas, plants were only 0.5 m tall. Morphological characteristics of plants in patch 9 were distinctly different to those recorded in other patches at this site (Figure 3.12). Plants in patch 9 were tall, in excess of 3 m in height, leaves were darker in colour with crinkled edges and flowers were yellow/green and more closely packed than those on surrounding plants.

At the Abbey Grounds site, six patches of hybrid plants were identified and mapped along the perimeter stream covering a total area of 25 m^2 (Figure 3.13). Of these, two were male-fertile (Table 3.7). The morphology of these plants was very different to those recorded at the A429 road verge site. All but patches 2 and 6 had darker green leaves than usual hybrid forms and leaves had crinkled edges. Flowers were a rich cream in colour and were unusually compactly arranged (Figure 3.14). Patches 2 and 6, on cytological examination, were found to be hexaploid (2n = 66), whilst all other patches were tetraploid (2n = 44).

Table 3.6 **Chromosome number, sex expression and area covered by 12 patches of *F.* x *bohemica* plants at A429 road verge site, Cirencester.**

PATCH NUMBER	CHROMOSOME NUMBER	SEX EXPRESSION	AREA (m2)
1	2n = 66	male-sterile	150
2	2n = 66	male-sterile	30
3	2n = 66	male-sterile	90
4	2n = 66	male-sterile	24
5	2n = 66	male-sterile	35
6	2n = 66	male-sterile	21
7	2n = 66	male-sterile	21
8	2n = 66	male-sterile	114
9	2n = 44	male-sterile	30
10	2n = 66	male-sterile	72
11	2n = 66	male-sterile	32
12	2n = 66	male-sterile	69
Total area			688

Table 3.7 **Chromosome number, sex expression and area covered by 6 patches of *F.* x *bohemica* plants at Cirencester Abbey Grounds.**

PATCH NUMBER	CHROMOSOME NUMBER	SEX EXPRESSION	AREA (m2)
1	2n = 44	male-sterile	1.0
2	2n = 66	male-fertile	16.0
3	2n = 44	male-sterile	3.0
4	2n = 44	male-sterile	1.5
5	2n = 44	male-sterile	1.0
6	2n = 66	male-fertile	3.0
Total area			25.0

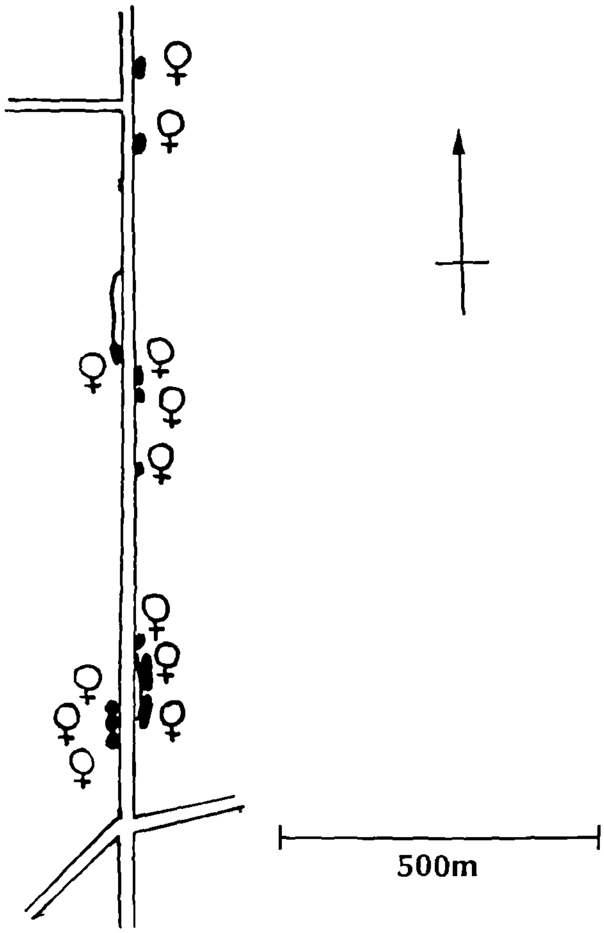


Figure 3.11 Plan of A429 survey site, Cirencester showing location of individual patches of hybrid plants along the 1 km stretch of roadside verge. Scale as shown.

Figure 3.12 Morphological features of hybrid plants in adjacent patches from A429 road verge survey site, Cirencester. Plants in the foreground (on the right of the photograph) with larger leaves are from patch 8 (2n = 66), plants to the left of the photograph are from patch 9 (2n = 44). Note smaller, darker coloured leaves with crinkled edges in patch 9.

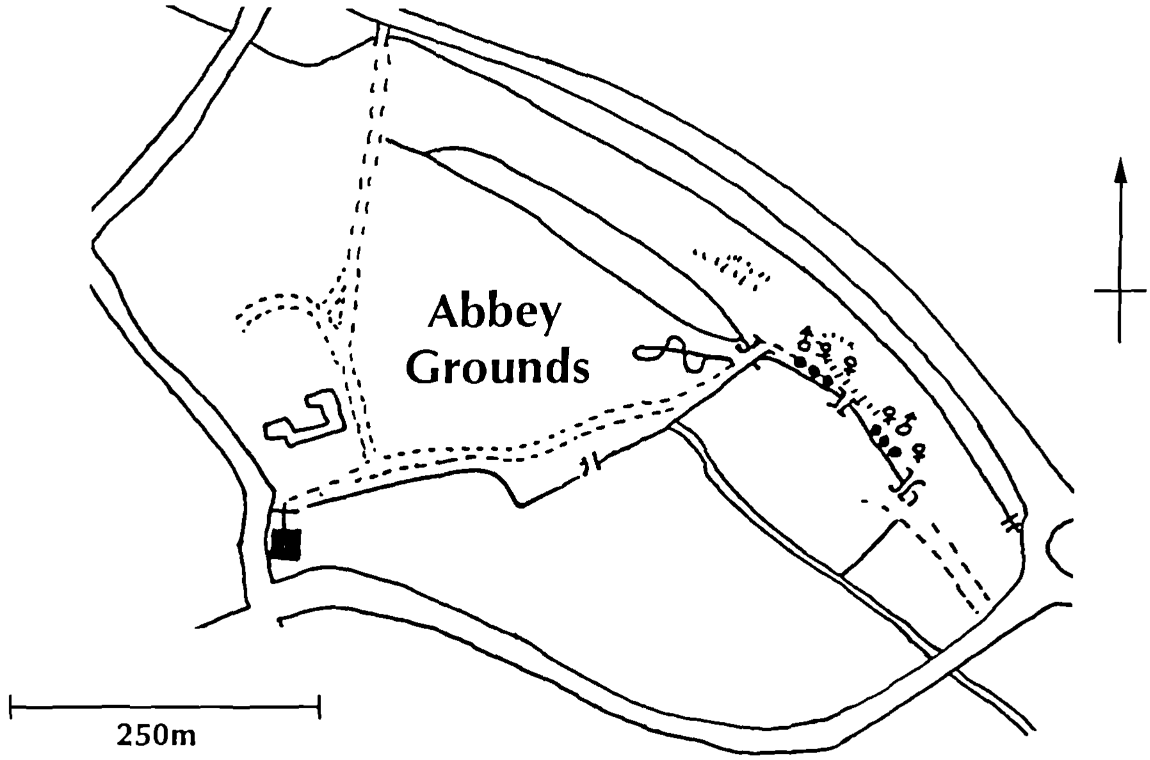


Figure 3.13 Distribution of hybrid *F.* x *bohemica* plants in Cirencester Abbey Grounds. Scale as shown.

Figure 3.14 Morphological characteristics of male-sterile (2n = 44) plants at Cirencester Abbey Grounds showing an unusually compact arrangement of flowers and crinkled edges to leaves.

3.4 DISCUSSION

A complex relationship between species within the *Fallopia* genus has been established. Whereas it has been previously assumed that all *F. japonica* in the British Isles is male-sterile and no sexual reproduction takes place, recent studies have shown that hybridisation does occur with a number of male-fertile species within the *Fallopia* genus (Bailey, 1994; Bailey *et al.*, 1995). Much of the seed produced on *F. japonica* plants in the British Isles can be accounted for by the *F. japonica* x *F. baldschuanica* hybrid (Bailey, 1997). However, the viability of this seed and subsequent survival of seedlings in the wild is assumed to be low to non-existent as only one live plant of this constitution has ever been recorded in the British Isles (Bailey, 1992). A similar situation exists in the USA where the majority of seeds produced on *F. japonica* plants are *F. baldschuanica* hybrids and seedling survival in the wild is not observed (Seiger, 1997). Although the origin of *F.* x *bohemica* hybrid plants in the British Isles is not known, hybridisation routes are possible between various *Fallopia* congeners (Table 3.3) forming *F.* x *bohemica* hybrids.

This study examined the population of the hybrid *F.* x *bohemica* in the British Isles and its distribution. In particular, the extent to which *F.* x *bohemica* is now recorded throughout the British Isles, the population characteristics of these plants in terms of sex expression and genetic constitution and the implications that hybrid plants may have for future management are discussed. The results of the survey show that *F.* x *bohemica* is widely distributed in the British Isles. As only one location was duplicated in the responses received, it is possible that the hybrid is still under-recorded in the British Isles. Looking at hybrid sites on a smaller scale in the Cirencester studies, a wide range of hybrid forms may exist at a single location. The range of hybrid types is discussed in more detail below.

This study has identified that spatial scale is important in mapping the distribution of a plant species. The records for hybrid plants when plotted at a 10 km square scale merely show presence of the plant in that square. The responses from Surrey indicate that plotting records at a 10 km square scale fails to show numbers of records and it is necessary to plot at a larger scale in order to reflect greater detail in distribution patterns. Plotting the Surrey records at a 1 km square scale has revealed that groupings of hybrid plants exist. For example, a cluster of hybrid plants are observed along the River Wey Navigation through Guildford. This pattern mimics the pattern of *F. japonica* distribution which is also prevalent along river and stream corridors and raises the question of the potential for vegetative dispersal *via* watercourses. The Cirencester studies also show that when hybrid locations are investigated at the individual patch scale, co-existence of different hybrid forms are observed within a patch. It would appear that the hybrid forms observed in these studies demonstrate co-dominance.

Thirty two percent of *F.* x *bohemica* plants recorded in this survey were identified as male-fertile plants, doubling the number of male-fertile plants recorded to date. This may still be an under-estimation of the total population as sex of plants can only be determined on the basis of flower morphology and timing of collection is critical. Not all the respondents sent flower samples therefore a number of hybrid locations are still unidentified in terms of sex expression. It is possible that male flowers were used as a determinant of hybrid plants as 94% of flowers returned in the survey were from male-fertile plants. There may therefore be an under recording of hybrid plants of male-sterile (female) constitution due to a lack of any easy means of recognition.

From the survey data, the occurrence of hexaploid hybrids determined by chromosome counts (Bailey, pers. comm.) is greater than that for tetraploid plants (26 and 7 respectively). This is confirmed by studies at the Cirencester A429 road verge site where hexaploid plants outnumbered tetraploid plants 11:1. Hexaploid hybrids must have one octoploid parent. The only contender for this in the British Isles would be octoploid *F. japonica* as a female parent. Tetraploid hybrids must have tetraploid parents, either *F. sachalinensis* or *F. japonica* var. *compacta* unless the result of imported seed with tetraploid *F. japonica* as a parent. At Cirencester Abbey Grounds, tetraploid plants outnumbered hexaploid plants 4:2. This could be explained to some degree by local vegetative spread. Both sites are subject to disturbance, at the A429 site due to mowing along the road verge which could result in spread by cut stems and at the Abbey Grounds site, where plants were growing along a watercourse at the perimeter of the Abbey Grounds, where fragments of rhizome and cut stems could be transported downstream. It is now well established that in Britain at least, *F. japonica* is spread exclusively by vegetative means by transport of stem and rhizome fragments (Chapter 2, Brock and Wade, 1992, Brock *et al.*, 1995). What is not yet known is the vegetative regeneration potential of hybrid material. This will be explored in detail in Chapter 4.

It has been established that any seed produced by *F. japonica* plants in the British Isles is of hybrid origin (Bailey, 1989, Bailey and Stace, 1992, Bailey and Conolly, 1991). The viability of this seed could be important in the potential spread of hybrid *Fallopia* taxa. Large amounts of seed are indeed produced by *F. japonica* and this seed is almost exclusively the result of pollination by *F. baldschuanica* (Bailey, 1988). A similar situation is reported in the USA (Seiger, 1997) where seed produced on *F. japonica* plants has been found to be *F. japonica* x *F. baldschuanica* hybrid.

Spontaneous germination has been documented at sites where *F. japonica* and *F. sachalinensis* grow together (Bailey *et al.*, 1995) and research is ongoing exploring the conditions governing both the germination and survival of these seeds in the wild. Bailey (1994; 1997) reports that survival of seedlings is poor in the British Isles and that spread of the *Fallopia* taxa by seed is unlikely to provide a substantial means of dispersal. This view is supported by Seiger (1997) who reported that despite seed germination success under laboratory conditions, seedling establishment and subsequent survival in the wild has not to date been observed in the USA. Seeds play a major role in the dispersal of the plant in its native range and seedling survival has been well documented by Maruta (1976; 1983; 1994). That seeds produced in the introduced ranges of the plant are viable under laboratory conditions but are not observed establishing in the wild poses several questions.

- Does seedling survival in the wild in Japanese populations indicate a genetic predisposition for survival which is not encountered in seeds in the British Isles?
- If seedling survival rates are negligible what mechanisms of dispersal have enabled the hybrid *F.* x *bohemica* to spread throughout the British Isles?
- What are the implications in terms of future management of these species?

Certainly, the morphological variation observed in Japanese herbarium material would suggest that the specific variety of *F. japonica* which was introduced to the British Isles is not typical of Japanese *P. cuspidatum* populations (pers. obs.). Adachi (pers. comm.) has confirmed that the plants studied by Maruta (1994) in her work on seedling establishment of *P. cuspidatum* on Mount Fuji were not of the type regarded in the British Isles as typical *F. japonica* but more closely resembled *F. japonica* var. *compacta*. Indeed, the genetic constitution of seed from Japanese plants has to date been found to be tetraploid (2n = 44) (Bailey, pers. comm.). The majority of seed produced in the British Isles has the genetic constitution 2n = 54, being of hybrid origin with *F. baldschuanica.* These genetic differences could account for the lack of seedling establishment observed in Britain. However, there is still an anomaly in that this seed is viable and has been grown in the laboratory successfully in both Britain and the USA. Specific conditions for seedling survival have not yet been addressed.

Research into the genetic constitution of the different varieties is continuing (Bailey, pers. comm.) with new molecular techniques such as Polymerase Chain Reaction Random Amplified Polymorphic DNA (PCR RAPDs). DNA extracted from fresh plant material is processed with selected genetic 'primers' (essentially small strands of DNA) and multiple copies of DNA are reproduced. These are then separated on electrophoretic plates to produce banding patterns which correspond to individual species. Some success has already been made in identifying specific banding patterns for *F. japonica*, *F.* x *bohemica*, *F. sachalinensis* and *F. japonica* var. *compacta* . Results to date show a very limited genetic base for *F. japonica* in the British Isles (Bailey *et al.*, 1995). Further research is in progress to refine these techniques in order to explore the genetic history of this group of species more fully.

The origin of the *F.* x *bohemica* hybrids is not known and further work will be necessary to establish whether these hybrids have arisen spontaneously or whether they have been introduced *via* horticulturists as a separate variety. Either way, a complete picture of the distribution of the plants throughout the country provides an excellent starting point to assess future changes in aiding understanding of their spread. One possible source of hybrids would be seed collections from gardens. As *F. japonica* var. *compacta* and *F. sachalinensis* are self-incompatible (Bailey 1990), seed collected from open-pollinated plants is invariably of hybrid origin. Any seed saved by gardeners in this country would be expected to be hybrid and this could be an important source of hybrid plants, particularly if raised in a glasshouse and later planted out. The range of plants recorded at the Abbey Gardens in Cirencester for example would support this theory. A range of *Fallopia* species is also seen in the gardens at Buckingham Palace. Although no planting records for the *Fallopia* species exist at Buckingham Palace, all three parental types are present (*F. japonica*, male and female *F. sachalinensis* and male and female *F. japonica* var. *compacta*) in addition to both male and female *F.* x *bohemica* plants. The occurrence of a larger percentage of

F. x *bohemica* recorded in this survey from parks and gardens than for *F. japonica* or *F. sachalinensis* would also support this hypothesis.

There is the potential for hybrids other than *F.* x *bohemica* to be formed by this group of species (Table 3.3). However, their distribution is limited. For example *F. japonica* x *F. japonica* var. *compacta* is known only from one site in Cornwall. Morphologically this taxon is very similar to *F. japonica* and the Cornish plant was only found because it bore hermaphrodite flowers (Bailey and Conolly, 1991). Male-sterile clones of this constitution could easily go unnoticed. The presence of male-fertile flowers on hybrid plants could also provide an important source of pollen for back-crossing with *F. japonica* thereby adding a new dimension to the spread of these species.

In addition to the hexaploid hybrids, tetraploid forms of *F.* x *bohemica* also occur as seen in the Cirencester studies. In Britain, these tetraploid hybrids would be expected to be of the constitution *F. japonica* var. *compacta* x *F. sachalinensis* (since *F. japonica* var. *compacta* is the only tetraploid *F. japonica* known from this country). If imported as seed from Japan or Europe there is a possibility that one parent could be tetraploid *F. japonica* var. *japonica*.

Bailey and Stace (1992) reported that whilst all the hexaploid hybrids had a very low fertility the tetraploid hybrids had a fertility comparable with the tetraploid species. It has been found that in spite of the very low fertility of these hexaploid hybrids that small amounts of fertile pollen are produced that are in turn capable of producing viable seed. Plants produced by back-crossing with the parental taxa could be expected to exhibit an almost continuous range of morphological variation between the original parents, making identification of taxa very difficult. It is proposed that such a series of secondary hybridisations account for the unusual range of plants found in the Cirencester sites. Further rounds of hybridisation *via* back-crossing of existing hybrids with either *F. japonica* var. *japonica* or *F. sachalinensis*, or indeed between hybrids may be expected to occur (Table 3.8).

Table 3.8 Hybridisation routes *via* back-crossing of existing tetraploid hybrids

FEMALE PARENT		MALE PARENT		HYBRID	OCCURRENCE
F. japonica (2n = 88)	x	*F.* x *bohemica* (2n = 44)	→	*Hybrid* (2n = 66)	Not known
F. x *bohemica* (2n = 44)	x	*F.* x *bohemica* (2n = 44)	→	*Hybrid* (2n = 44)	Not known
F. japonica var. *compacta* (2n = 44)	x	*F.* x *bohemica* (2n = 44)	→	*Hybrid* (2n = 44)	Not known
F. x *bohemica* (2n = 44)	x	*F. japonica* var. *compacta* (2n = 44)	→	*Hybrid* (2n = 44)	Not known
F. sachalinensis (2n = 44)	x	*F.* x *bohemica* (2n = 44)	→	*Hybrid* (2n = 44)	Not known
F. x *bohemica* (2n = 44)	x	*F. sachalinensis* (2n = 44)	→	*Hybrid* (2n = 44)	Not known

The impact that these plants may have on future control and management programmes for *F. japonica* is as yet uncertain. The role of seed production at present would appear to be a minor factor in the dispersal of these species. However, with increasing numbers of hybrid plants throughout the British Isles and potentially viable pollen from a variety of sources within the *Fallopia* genus, including potential back-crossing with parental material, the genetic constitution of seeds produced requires further consideration. A wider genetic variation within the species carries with it a greater probability of seedling viability under a particular set of conditions.

Clearly then, seed dispersal is not a major concern to environmental managers at present. The means of dispersal of hybrid plants however is a factor which requires further study, especially in consideration of results from Chapter 2 regarding the vegetative regeneration potential of *F. japonica*. If it is assumed that the hybrid plants have not arisen by spontaneous germination of seed, the potential for vegetative regeneration of these plants becomes strategically important. Chapter 4 investigates regeneration rates for rhizome and stem material of *F.* x *bohemica* plants in order to establish the potential for further spread by vegetative means.

3.5 CONCLUSIONS

- Prior to this survey, 60 locations of *F.* x *bohemica* were known in the British Isles. This survey has added a further 71 locations. In all, 131 localities have now been identified which translate into 81 10 km squares on the distribution map, many squares containing more than one site.
- Male-fertile plants of *F.* x *bohemica* have been identified at 46% of localities during this survey, although the Cirencester studies show that on a micro scale, individual plants within a patch of hybrids can exhibit different morphological characteristics. It is possible that there are many more male-fertile hybrid plants awaiting discovery in the British Isles.
- Records for *F.* x *bohemica* show a higher percentage occurrence in parks and gardens than either *F. japonica* or *F. sachalinensis* and a lower percentage occurrence in riparian habitats than *F. japonica.*
- *F.* x *bohemica* in the British Isles is generally hexaploid ($2n = 66$) (26 locations) although tetraploid plants ($2n = 44$) have now been identified from 7 locations.
- There is a large potential for back-crossing in this group of species both between hybrids and between hybrids and parental species. These hybrid forms represent a much more varied genetic base than that of *F. japonica.*
- Factors affecting the spread of hybrids in Britain are, firstly, availability of suitable pollen and secondly, the extent to which hybrids use vegetative regeneration as a means of dispersal. Vegetative regeneration of the hybrid and parental species is explored in Chapter 5.
- Although at present *F. japonica* hybrids are unlikely to spread by seed, the presence of male-fertile plants of various hybrid constitution and male-fertile *F. sachalinensis* and *F. japonica* var. *compacta* represent a significant contribution to the potential for sexual reproduction within these species. Environmental managers should be aware of the potential for dispersal *via* seed due to changing climatic conditions. The distribution of the hybrids in the British Isles has been shown to be more complex than at first realised. A systematic survey of target areas where clusters of hybrid plants have been identified could reveal a further increase in distribution records. The varied

genetic base which is becoming apparent in hybrid forms is likely to enhance the range of environmental conditions already tolerated by these plants with associated challenges in managing these species making control even more difficult.

4.0 THE REGENERATION POTENTIAL OF CONGENERS OF *FALLOPIA JAPONICA* FROM RHIZOME FRAGMENTS AND CUT STEM MATERIAL

4.1 INTRODUCTION

In contrast to the limited genetic base reported for *Fallopia japonica* in the British Isles, results gained from Chapter 3 suggest that the hybrid *F.* x *bohemica* is genetically diverse. A distribution survey of the hybrid (Chapter 3) has shown that male and female hybrid plants exist in the British Isles in both their tetraploid and hexaploid forms. Although the majority of hybrid plants recorded to date have been female and hexaploid, the potential exists for numerous back-crosses with parental species (*F. sachalinensis* and *F. japonica* var. *compacta*) and with other hybrid types. The potential for sexual reproduction has been demonstrated at Cirencester Abbey Gardens where both male and female hybrid plants co-exist and a wide range of morphological characteristics are observed within the hybrid population. However, although seed is frequently set by these *Fallopia* species and seed has been shown to be viable under laboratory conditions, no records of seedling survival and establishment in the wild have yet been substantiated in the British Isles (Bailey, 1994; 1997). Given that the hybrid *F.* x *bohemica* has been shown to exist at a number of locations throughout the British Isles and making the assumption that the potential for spread by seed is minimal, it is suggested that vegetative spread must provide the main means of dispersal.

For *F. japonica*, high regeneration rates have been shown for planted rhizomes and cut stem segments subjected to both aquatic and soil treatments (Chapter 2; Brock and Wade, 1992; Welsh Development Agency, 1998a; 1998b; Brock *et al.*, 1995). The ability of *F. japonica* to regenerate from vegetative fragments has been a major factor in its successful invasion of the British Isles. The hybrid survey described in Chapter 3 has demonstrated the extent to which hybrid plants now occur in Britain and the habitat types in which these plants are frequently found. Although the percentage of hybrids which are recorded from parks and gardens is greater than that for *F. japonica*, suggesting that hybrids may have been intentionally planted, nevertheless, hybrid plants are also found throughout the wider environment along road verges, railway embankments and river corridors. As it is unlikely that these plants have arrived *via* seed dispersal, dispersal *via* vegetative regeneration is indicated. The extent to which hybrid material regenerates vegetatively will be significant in determining the future pattern of distribution and spread for this group of species. Therefore a series of greenhouse studies were undertaken to assess the potential for vegetative reproduction in *F.* x *bohemica* and its parents, *F. japonica* var. *compacta* and *F. sachalinensis.*

4.1.2 Aims and objectives

In order to achieve an understanding of the dispersal and regeneration routes for this group of *Fallopia* species, information is needed regarding the regeneration potential of vegetative material of species related to *F. japonica* including the hybrid *F.* x *bohemica*, (the major hybrid type in the British Isles), and its potential male parents either *F. sachalinensis* or *F. japonica* var. *compacta.* The hybrids *F. japonica* x *F. baldschuanica* and *F. sachalinensis* x *F. japonica* var. *compacta* have not been included in this study as only one plant of each type exists in the wild, the former at railway sidings in Haringey, north London (Bailey, 1992), the latter in Cornwall (Bailey and Conolly, 1991). *F.* x *bohemica* however, is becoming well distributed throughout the British Isles and there are management issues which need to be informed by both biological and cytological studies. Routes of hybridisation and the distribution of the hybrid have been described in Chapter 3, this chapter aims to promote the understanding of the means of dispersal of the hybrid and its parents through vegetative regeneration trials. More specifically the objectives of this study are to:

- assess the regeneration potential of rhizome and stem fragments of *F.* x *bohemica*, in terms of regeneration success and subsequent growth
- investigate whether there is a minimum and optimum size of fragment required for successful regeneration from rhizomes
- investigate whether segments obtained from different positions on the stem influence regeneration success and subsequent growth from cut stems
- investigate the extent to which position of nodes on the stem influences regeneration success and subsequent growth
- establish whether environmental conditions influence the regeneration success of cut stems, in particular the extent to which stems of hybrid plants regenerate in an aquatic or soil medium
- establish whether there is a difference in regeneration potential, regeneration period or subsequent growth between male and female plants of *F.* x *bohemica*

- assess the regeneration potential of rhizome and stem fragments of *F. sachalinensis* and *F. japonica* var. *compacta* in terms of regeneration success and subsequent growth
- understand the invasive potential of rhizome and stem fragments of the hybrid *F.* x *bohemica* and related species in order to implement effective management.

4.2 METHODS

4.2.1 Introduction

A series of greenhouse studies were undertaken following the methods described in Chapter 2. Two studies were carried out. The first, using two sources of *F.* x *bohemica* hybrid material, allowed comparisons to be made between hybrid material of unknown parentage collected from the wild and hybrid material of known genetic constitution from a collection at Leicester University (artificial hybrid). The second study used material collected from a single location, Buckingham Palace Gardens where all four forms of this section of the *Fallopia* genus known in the British Isles were present (*F. japonica*, *F. sachalinensis*, *F. japonica* var. *compacta* and the hybrid *F.* x *bohemica*). Detailed explanations of each study follow in sections 4.2.2 and 4.2.3.

The studies took place over a three year period, 1994 to 1996. In order to provide comparable results with those gained for *F. japonica* in previous studies, collection of mature plant material was made in the autumn and the trials were run for a period of at least 30 days with planting in early September. In order that regeneration rates could be compared with those for *F. japonica* under comparable conditions, *F. japonica* material was included as a control in each of the trials. None of the material collected for these studies had been subjected to chemical treatment prior to collection.

Planting and recording procedure

For both studies, rhizome and stem material was prepared and planted according to the methods described in Chapter 2. As results from Chapter 2 indicated a continuing increase in regeneration at 30 days, the first study was observed for a longer period (56 days). Using the procedure devised by Brock and Wade (1992) fragments of the rhizome material were cut into measured sections and weighed. Planting procedure followed the methodology described in Chapter 2 with fifteen fragments of each rhizome length assigned randomly to three replicates in batches of five fragments. Cut rhizomes were planted in a 50:50 coir compost:vermiculite growing medium in flat trays in the greenhouse covered with 1-2 cm of the planting medium. Resulting growth was measured for height and number of leaves at intervals over a period of at least 30 days and the measurements recorded.

Stems were subjected to buried and water treatments under one light regime (direct sun) for the first study but were subjected to water only treatment in study two as the quantity of stem material available was limited and results from previous trials (Chapter 2) had identified water sun treatments as a reliable test for stem regeneration potential. Stem material was divided into three sections: "upper", "middle" and "lower" according to position on the stem. Each stem section was cut with an intact node at each end. Fifteen segments of each stem length were grouped in batches of five and randomly assigned to three replicates in each treatment for each plant type following the procedure described in Brock *et al.* (1995). Resulting growth from stem segments was recorded as shoot height and number of leaves at regular intervals throughout the trial according to the methodology described in Chapter 2. At the end of at least 30 days, the plants were harvested and taken to Leicester University for chromosome analysis in order to confirm the genetic constitution of the various plant types.

Statistical analysis

Following data collection, results were entered onto Excel spreadsheets and mean percentage regeneration rates were calculated for each of the treatments. Data for shoot height were transformed ($\log_{10}$) to equalise variances according to Day and Quinn (1989) and where appropriate were subjected to Analysis of Variance using StatView (Abacus Concepts Inc., 1992-95). Where significant differences were indicated ($p < 0.05$) Fischer's protected least significant difference (plsd) test was calculated to aid mean separation (Steel and Torrie, 1980).

4.2.2 Comparison of wild and artificial hybrids

The first study in which the regeneration rates and subsequent growth of shoots from hybrid plants were compared was undertaken in the autumn of 1994. A summary of rhizome and stem treatments is shown in Tables 4.1 and 4.2.

Rhizome treatment

Rhizome material was collected from three locations. The first location was Leicester University (National Grid reference SK 596030) where a collection of hybrids had been created by artificial fertilisation from known parents (Bailey, 1989). The female *F.* x *bohemica* material (artificial hybrid) from this location had been grown from seed in the laboratory and subsequently planted out. This hybrid was of known provenance, from female *F. japonica* and male *F. sachalinensis* parents and was therefore hexaploid (chromosome number 2n = 66) (Bailey, pers. comm.). The hybrid plant was well established at the time of collection having been growing outdoors for 5 years in a large container measuring approximately 9 m^3. The second collection was of male-fertile *F.* x *bohemica* (wild hybrid) from a road verge site at Cheswick Green, Birmingham, adjacent to the A34/M42 junction (National Grid reference SP 145757). Identification was made from morphological characteristics of mature leaves and flowers. The plants at this site were well established and covered an area of approximately 50 m^2. The collection of *F. japonica* material was made from the site at Snell's Nook Lane, Nanpantan (National Grid reference SK 504174) used in the greenhouse study reported in Chapter 2. Collections from each location were made during late August and early September 1994.

Table 4.1 Summary of rhizome treatments

Three replicates of 5 samples (n = 15) of each of 4 levels of rhizome fragment length 1, 2, 4 and 8 cm for each plant type (N = 180) .

TREATMENT - PLANTING											
ARTIFICIAL HYBRID				WILD HYBRID				*F. JAPONICA*			
1 cm (n=15)	2 cm (n=15)	4 cm (n=15)	8 cm (n=15)	1 cm (n=15)	2 cm (n=15)	4 cm (n=15)	8 cm (n=15)	1 cm (n=15)	2 cm (n=15)	4 cm (n=15)	8 cm (n=15)

Stem treatment

Stem treatments used material from two of the sources described above, male fertile *F.* x *bohemica* from a road verge site at Cheswick Green, Birmingham, adjacent to the A34/M42 junction (National Grid reference SP 145757) (wild hybrid) and *F. japonica* from the site at Snell's Nook Lane, Nanpantan (National Grid reference SK 504174).

Collections from each location were made during late August and early September 1994. A summary of stem treatments is shown in Table 4.2.

Table 4.2 Summary of stem treatments

Three replicates of 5 (n = 15) of each of three stem segment lengths UPPER, MIDDLE and LOWER (U, M, L) each consisting of two nodes, *upper* and *lower* (*u*, *l*), were assigned to two treatments, BURIED SUN and WATER SUN for each plant type, WILD HYBRID and *F. JAPONICA*. (N = 180).

TREATMENT - BURIED SUN						TREATMENT - WATER SUN					
WILD HYBRID			*F. JAPONICA*			WILD HYBRID			*F. JAPONICA*		
U (n=15)	M (n=15)	L (n=15)	U (n=15)	M (n=15)	L (n=15)	U (n=15)	M (n=15)	L (n=15)	U (n=15)	M (n=15)	L (n=15)
u l	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*

4.2.3 Comparison of hybrids with parental types

The second study was undertaken in the autumn of 1996 to investigate the regeneration potential of the hybrid *F.* x *bohemica* and its parents, *F. japonica*, *F. sachalinensis* and *F. japonica* var. *compacta*. Samples of fresh stem and rhizome material from *F. sachalinensis*, *F. japonica*, *F.* x *bohemica* and *F. japonica* var. *compacta* plants were collected from Buckingham Palace Gardens (National Grid reference TQ 287795) in the autumn of 1996. In addition, leaf and flower material was collected from each plant in order to identify the plants from morphological characteristics. Plant variety was determined by morphological characteristics of leaves according to the methodology described in Chapter 3 and sex of plants was determined by flower parts, male plants had flowers with exserted anthers. In order to confirm the genetic constitution of the various plant types, live plant material resulting from the trial was taken for chromosome analysis (Bailey pers. comm.). A summary of plants collected with confirmation of sex and chromosome number is presented in Table 4.3.

Although there are no planting records for the Palace Gardens, it is known that these various forms of *Fallopia* species have been present in the garden since at least 1970 (Mark Lane pers. comm.). Collecting plants from a single location minimised the effects of any variations in growth conditions with respect to climatic factors, soils and management. For the purposes of the regeneration trials, it was also important to ensure that the plants had not been treated with herbicide as this could adversely affect the growth of rhizome material. The *Fallopia* species at Buckingham Palace were managed only by mechanical means (i.e. by mowing, cutting or strimming) late in the season to remove above ground material which would otherwise look untidy (Mark Lane, pers. comm.).

Table 4.3 Variety, sex and chromosome number of plants from Buckingham Palace Gardens used in the study.

VARIETY	SEX	CHROMOSOME NUMBER
F. x *bohemica*	male-sterile (female)	2n = 66
F. x *bohemica*	male-fertile	2n = 66
F. japonica	male-sterile (female)	2n = 88
F. sachalinensis	male-fertile	2n = 44
F. japonica var. *compacta*	male-fertile	2n = 44

Rhizome treatment

For the rhizome study, results of previous trials had identified (Chapter 2) that maximum regeneration rates were achieved by 4 cm lengths of rhizome material. As the amount of material available for this study was limited, 4 cm rhizome lengths were selected as the maximum size for this treatment. In order to identify the minimum rhizome fragment size which would regenerate, 1 cm fragments were also selected. A summary of treatments is shown in Table 4.4.

Table 4.4 Summary of rhizome treatments

Three replicates of 5 samples (n = 15) for each of 2 levels of rhizome fragment length (1 and 4 cm) for each plant type (N = 150) .

TREATMENT - PLANTING									
F. x *bohemica* (male)		*F.* x *bohemica* (female)		*F. sachalinensis* (male)		*F. japonica* var. *compacta* (male)		*F. japonica* (female)	
1 cm (n=15)	4 cm (n=15)	1 cm (n=15)	4 cm (n=15)	1 cm (n=15)	4 cm (n=15)	1 cm (n=15)	4 cm (n=15)	1 cm (n=15)	4 cm (n=15)

Stem treatment

As the amount of material available in this study was limited, stems were subjected to a single water sun treatment. The decision to carry out this treatment was based on results gained from Chapter 2 which indicated that a water sun treatment was most successful in promoting rapid regeneration. Stem material collected from the Palace Gardens was assigned to treatments as shown in Table 4.5. Procedures for planting, recording and analysis of both stem and rhizome treatments were carried out as described in section 4.1.1.

Table 4.5 Summary of stem treatments

For each plant type, three replicates of 5 (n = 15) of each segment length UPPER, MIDDLE and LOWER (U, M, L) each consisting of two nodes, *upper* and *lower* (*u*, *l*), were assigned to one treatment WATER SUN (N = 270).

TREATMENT - WATER SUN														
F. x bohemica (male)			*F. x bohemica* (female)			*F. sachalinensis* (male)			*F. japonica* var. *compacta* (male)			*F. japonica* (female)		
U (n=15)	M (n=15)	L (n=15)	U (n=15)	M (n=15)	L (n=15)	U (n=15)	M (n=15)	L (n=15)	U (n=15)	M (n=15)	L (n=15)	U (n=15)	M (n=15)	L (n=15)
u l	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*	*u l*

4.3 RESULTS

4.3.1 Study 1

Rhizome treatment

In terms of overall regeneration success at harvest (56 days after planting), 100% regeneration success was observed for 2, 4 and 8 cm fragments of both artificial and wild hybrid source material (Figure 4.1). Initially wild hybrids showed a higher percentage regeneration of 1 cm fragments compared to artificial hybrids but this was not sustained to harvest (Figures 4.2 and 4.3). For 1 cm fragments, shoot death occurred in wild hybrid plants throughout the trial which accounts for the fall in percentage regeneration success seen after 10 days. However, the total percentage of 1 cm rhizome fragments which had regenerated by harvest was 80% for wild hybrids compared to 20% for artificial hybrids (Figure 4.1).

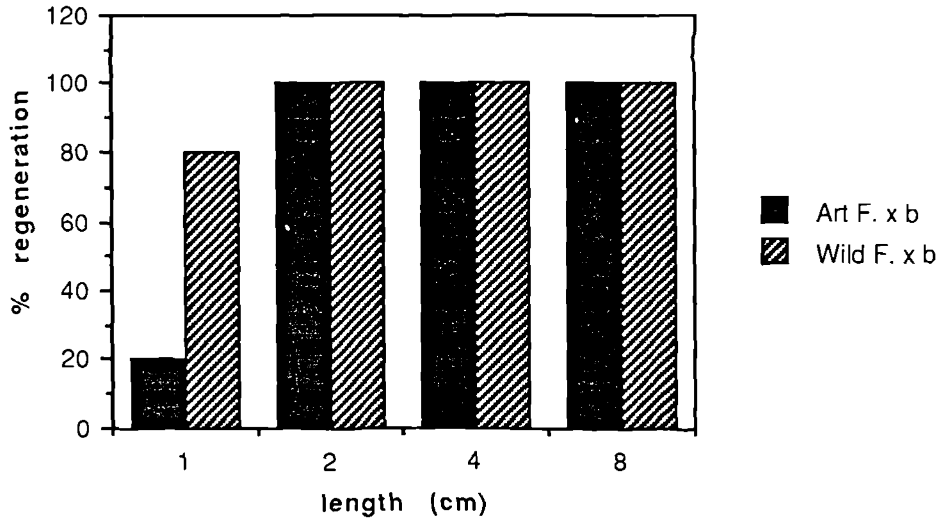


Figure 4.1 Percentage regeneration at harvest of artificial and wild *F.* x *bohemica* rhizome fragments by rhizome length. Key Art F. x b = artificially created *F.* x *bohemica* plants; Wild F. x b = wild collected *F.* x *bohemica* plants.

The timing of shoot emergence for planted rhizome fragments of wild and artificial hybrids are shown in Figures 4.2 and 4.3. Shoot emergence was realised 6 days after planting for wild hybrids whereas artificial hybrids did not produce visible shoots until 13 days. This was true for all fragment lengths of wild hybrid and for 2, 4, and 8 cm lengths of artificial hybrids. Shoot emergence was not observed in 1 cm fragments of artificial hybrid until 34 days after planting. This was possibly due to short lengths being predominantly internode material and consequently lacking in developed buds. *F. japonica* shoots in this study began to emerge at 6 days for 2 cm fragments and 10-13 days for other fragment lengths. This rate of emergence was more rapid than that observed for *F. japonica* in earlier trials (Chapter 2) where shoots produced by 4 and 8 cm fragments were not observed until 12 days after planting.

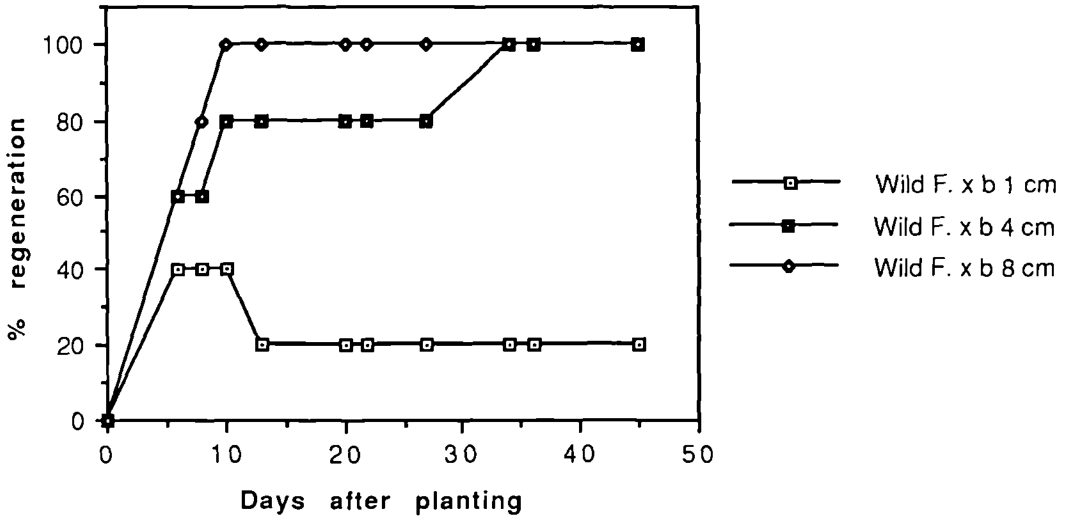


Figure 4.2 Timing of shoot emergence for wild hybrid *F.* x *bohemica* rhizome fragments. (2 cm fragments showed results identical to those from 4 cm fragments)

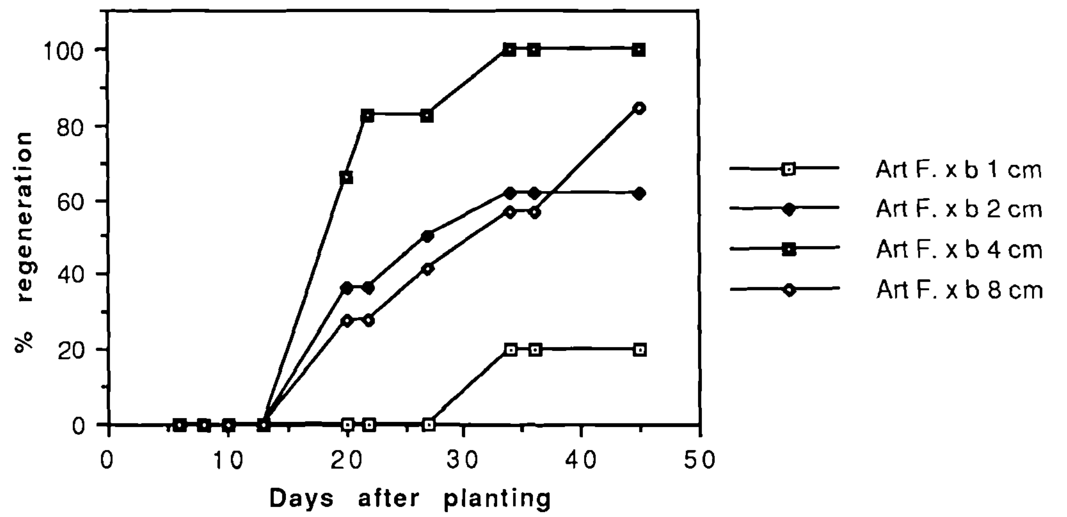


Figure 4.3 Timing of shoot emergence for artificial hybrid *F.* x *bohemica* rhizome fragments.

The time required to reach a 50% regeneration success rate was achieved most rapidly for 2, 4 and 8 cm lengths of wild hybrid material (6 days after planting). Artificial hybrid 4 cm fragments achieved 50% regeneration by 20 days, 2 and 8 cm fragments by 34 days. A regeneration rate of 50% was not achieved by 1 cm fragments from either source possibly due to lack of bud development on shorter fragments. *F. japonica* rhizomes achieved a 50% regeneration success rate for 4 cm fragments 24 days after planting and 2 and 8 cm fragments by 30 days.

Height of shoots produced by 4 cm rhizome fragments of artificial and wild hybrids are shown in Figure 4.4. Shoots were produced earlier for wild hybrids than for artificial hybrids (6 days and 20 days respectively). By 27 days no significant differences in shoot height were observed but by harvest (56 days) shoots from artificial hybrids were significantly taller ($p < 0.05$) than those from wild hybrid rhizomes. For 1, 2 and 8 cm fragments, a similar trend was observed with wild hybrid rhizomes producing taller shoots earlier than artificial hybrids. Throughout the trial, shoots produced by hybrid rhizomes from both sources were significantly taller ($p < 0.05$) than those produced by fragments of *F. japonica* rhizomes.

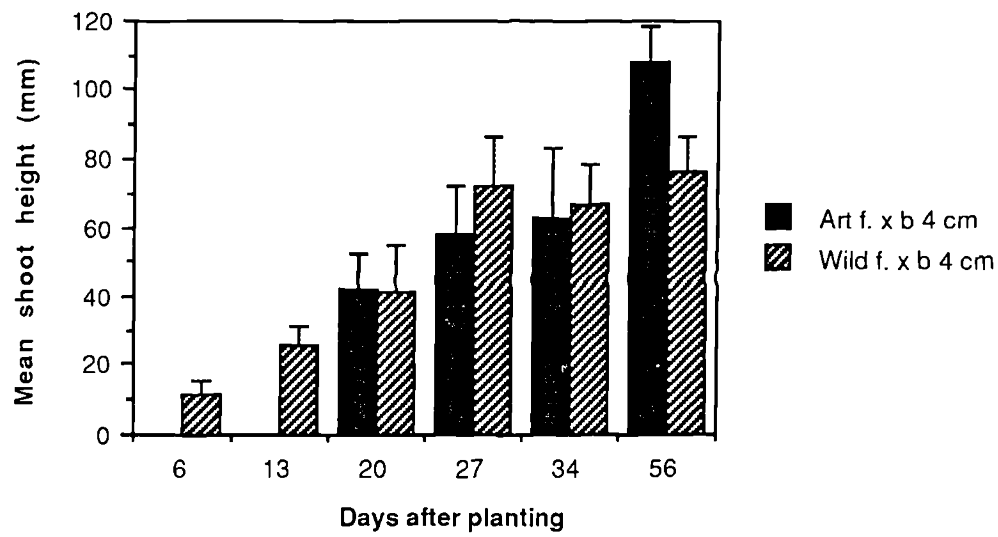


Figure 4.4 Height of shoots produced by 4 cm rhizome fragments of artificial and wild *F.* x *bohemica* during the trial period. Data presented are mean values ±1SE (n = 15)

Following the trend in shoot production, wild hybrids produced leaves more rapidly than artificial hybrids although by the end of the trial, no significant difference in leaf numbers were observed for any of the fragment lengths. Numbers of leaves on shoots produced by 2 cm rhizome fragments are shown in Figure 4.5.

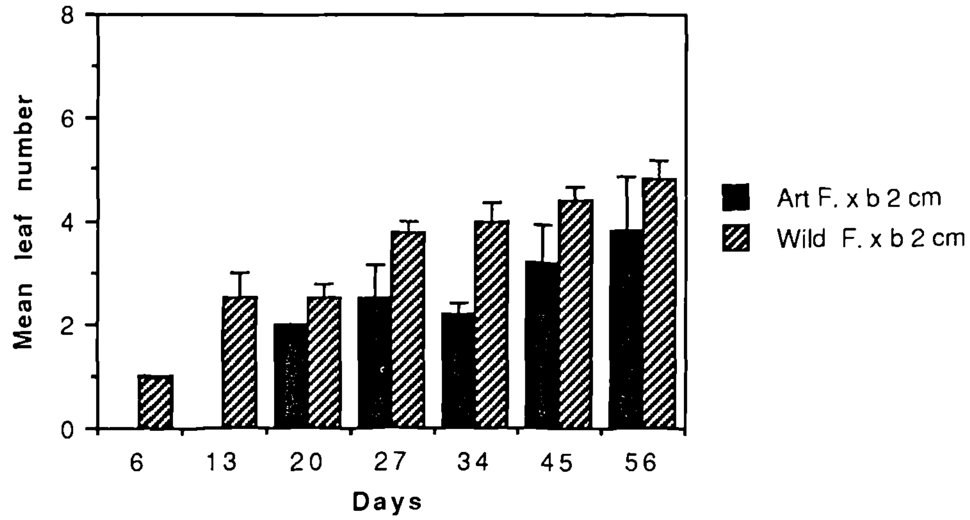


Figure 4.5 Number of leaves produced by 2 cm fragments of rhizomes of artificial and wild *F.* x *bohemica* over the trial period. Data presented are mean values ±1SE (n = 15)

The length: mean fresh weight relationship for rhizome fragments for each of the two hybrid plant types are presented in Figure 4.6. A non-linear relationship between fragment length and weight is observed due to variation in rhizome diameter, despite random allocation of rhizome to fragment length groups. Fragment weight for 1 cm rhizomes ranged between 0.5 - 1.0 g. Weight for 8 cm fragment lengths ranged between 3.0 - 6.5 g. Mean fresh weight of 1 and 2 cm fragments were comparable for each of the plant types whereas weights for 4 and 8 cm rhizome fragments from artificial hybrid plants were higher than those for *F. japonica* or wild hybrids. Mean weight of 1 cm fragments for wild hybrids was 0.9 g and for artificial hybrids was 0.6 g. These fragment lengths showed overall regeneration rates of 80% and 20% respectively. The minimum mean weight of hybrid rhizome material which regenerated successfully was therefore 0.9 g.

A summary of results for the rhizome treatments (Table 4.6) shows that wild hybrid rhizome material in these trials produced shoots after the same time period as *F. japonica* (6 days after planting) but reached a 50% success rate for regeneration in considerably less time than *F. japonica* or artificial hybrid rhizomes (6, 27 and 34 days respectively). Leaf emergence was also more rapid for wild hybrid plants (6 days after planting) although mean shoot height attained was not significantly different between the plant types. These observations indicate a high potential for rapid regeneration by hybrid rhizome fragments.

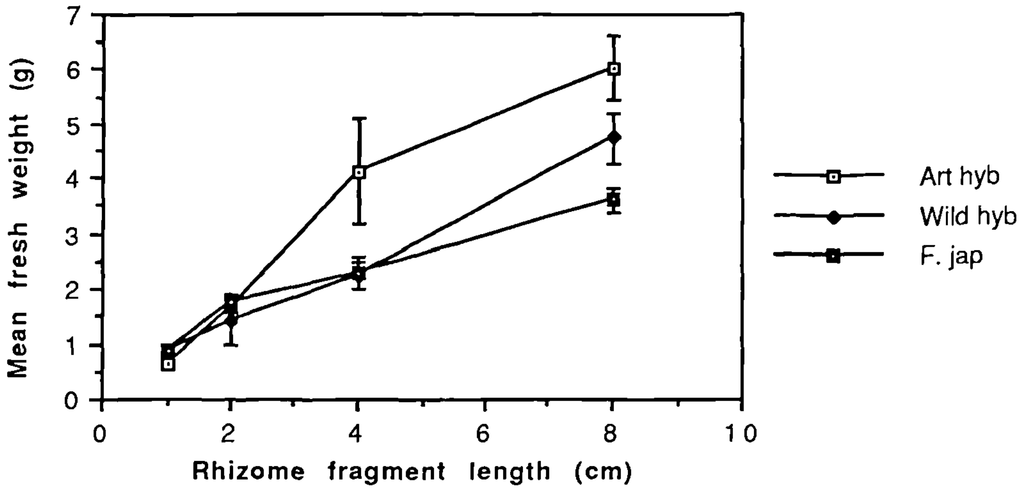


Figure 4.6 Relationship between mean fresh weight and rhizome fragment length in Study 1. Data presented are mean values ±1SE (n = 15). Key: Art hyb = artificial hybrid; Wild hyb = wild hybrid; F. jap = *F. japonica*.

Table 4.6 Summary of results from rhizome fragment treatments. Data presented are pooled for fragment length and mean values are given. Values followed by the same letter are not significantly different at the 95% significance level using Fischer's protected least significant difference test.

Characteristic	**Artificial hybrid (*F.* x *bohemica*)**	**Wild hybrid (*F.* x *bohemica*)**	***F. japonica***
Days to emergence	20	6	6
Days to 50% regeneration	20 - 34	6	27
% regeneration by harvest	20 - 100	80 - 100	60 - 100
Mean shoot height at harvest (mm) ±1SE	92.3 ±17.9[a]	72.9 ±4.5[a]	69.4 ±11.9[a]
Days to leaf emergence	20	6	20
Mean leaf number at harvest ±1SE	5.2±1.2	4.9±0.4	3.9±0.6

Stem treatment

Regeneration rates are shown in Figure 4.7 for *F.* x *bohemica* (wild) and *F. japonica* stems subjected to water and buried treatments. *F. japonica* stems subjected to water treatment gave the highest regeneration success throughout the trial. For both water and buried treatments *F. japonica* achieved a higher percentage regeneration rate than hybrid stems. Although the regeneration rate was higher for stems in the water treatment initially, after 13 days, hybrid stems subjected to buried treatment regenerated more successfully than those subjected to a water treatment. Shoot emergence was observed 6 days after planting for all treatments. Some shoot death occurred throughout the trial in water treatments which accounts for the falling rate of regeneration after 40 days. This was not observed in previous trials (Chapter 2) which were only continued for 39 days..

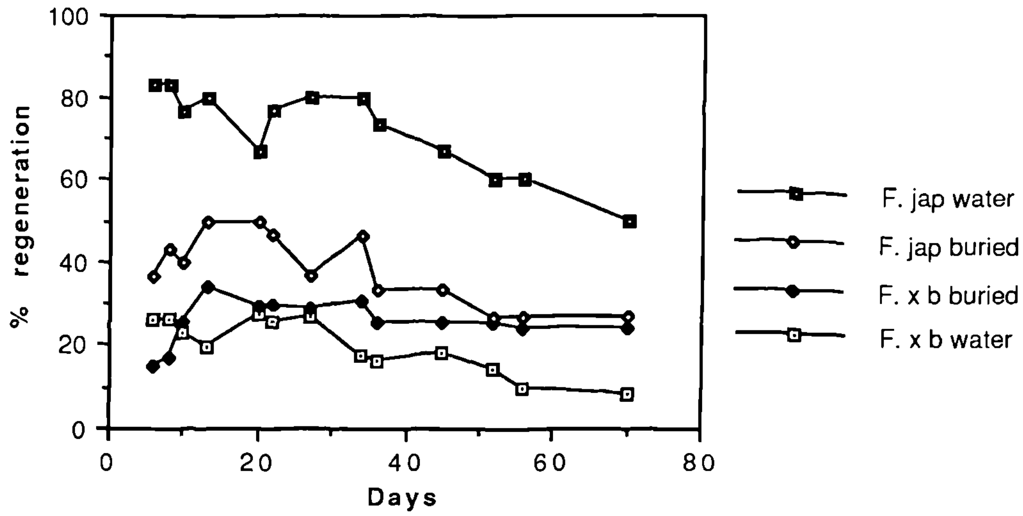


Figure 4.7 Percentage regeneration rates over time for *F.* x *bohemica* and *F. japonica* stems subjected to water and buried treatments. Data presented are mean values pooled for stem segment and node (n = 90).

Lower stems of *F.* x *bohemica* subjected to water treatment achieved 53% regeneration success 6 days after planting, however, middle and upper stem segments failed to achieve 50% regeneration success from either upper or lower nodes throughout the trial. For *F.* x *bohemica* stems subjected to the buried treatment, lower stem segments took 13 days to achieve 50% regeneration success. Middle and upper hybrid stem segments failed to achieve 50% regeneration success during the trial. No significant differences in shoot production were observed between upper and lower nodes throughout the trial.

For *F. japonica*, stems subjected to the water treatment had achieved 50% regeneration success for all segments 6 days after planting, with middle segments (both nodes) and lower segments (upper nodes) showing a 100% regeneration by this time. Stems subjected to the buried treatment reached 50% regeneration by 13 days for middle and lower segments but upper segments failed to achieve a 50% regeneration rate during the trial. Overall percentage regeneration success at harvest for the two treatments are shown in Figure 4.8 and include all segments which produced shoots throughout the trial. Regeneration success was greater for *F. japonica* than for *F.* x *bohemica* stems in both water and buried treatments. Results for *F. japonica* in this trial were comparable to those from earlier trials (Chapter 2).

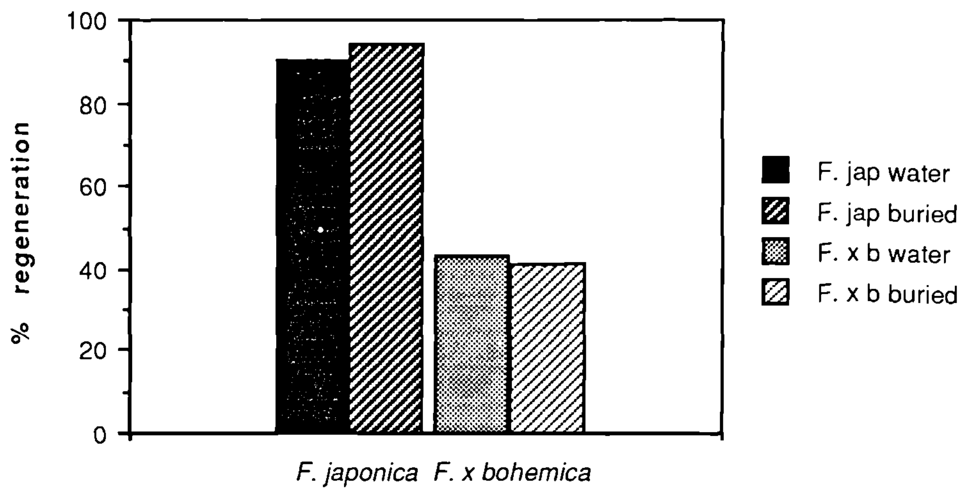


Figure 4.8 Percentage regeneration success at harvest for *F. japonica* and *F.* x *bohemica* (wild hybrid) stems subjected to water and buried treatments. Data presented are pooled for stem segment and node.

Significant differences were observed in shoot heights produced by *F.* x *bohemica* middle segment stems. Hybrid stems subjected to buried treatments produced significantly taller ($p < 0.05$) shoots than those subjected to water treatment. No significant differences were observed in height of shoots produced by *F. japonica* middle segment stems in buried and water treatments (Figure 4.9) and these were comparable with height of shoots produced from *F.* x *bohemica* middle segment stems subjected to buried treatments.

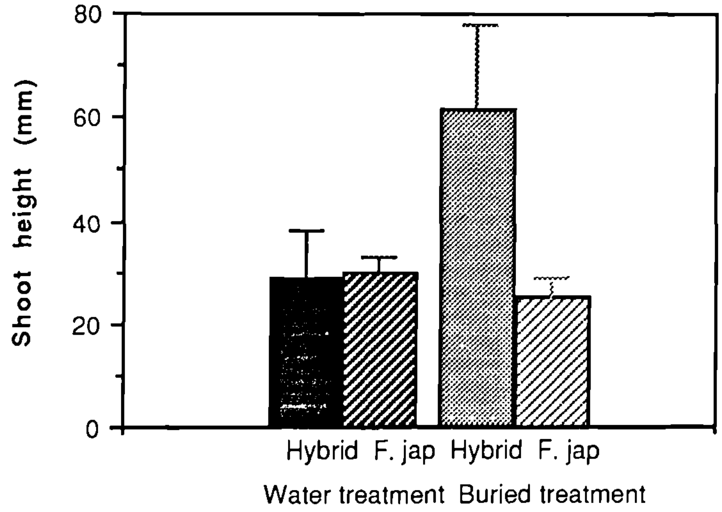


Figure 4.9 Shoot height produced by middle stem segments 34 days after planting for hybrid (*F.* x *bohemica*) and *F. japonica* stems subjected to buried and water treatments. Data presented are mean values ± 1SE pooled for nodes.

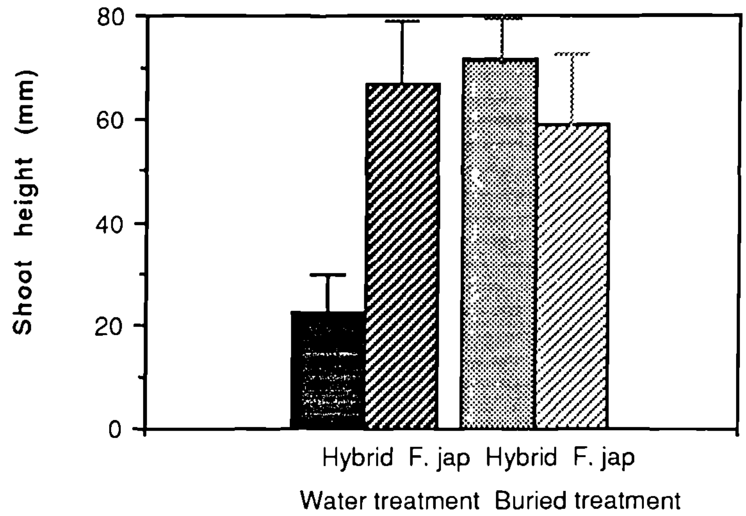


Figure 4.10 Shoot height produced by lower stem segments 34 days after planting for hybrid (*F.* x *bohemica*) and *F. japonica* stems subjected to buried and water treatments. Data presented are mean values ± 1SE pooled for nodes.

Figure 4.10 shows mean shoot height produced by lower stem segments 34 days after planting. In water treatments, both upper and lower segments of hybrid stems produced significantly less ($p < 0.05$) shoot height than *F. japonica* segments. Hybrid stems subjected to buried treatments produced significantly greater ($p < 0.05$) shoot height than all other treatments.

Table 4.7 shows summary results for the stem treatments. Pooled data allow comparison of results for the different plant types subjected to each treatment. Although shoot emergence was rapid for both plant types (6 days) a 50% regeneration success rate of all stem segments was only reached for *F. japonica*, for hybrid stems this was only achieved by lower stem segments.

Table 4.7 Summary of results from stem segment treatments. Data presented are pooled for segment and node, where appropriate range and mean values are given. Values followed by the same letter are not significantly different at the 95% significance level using Fischer's protected least significant difference test.

CHARACTERISTIC	BURIED TREATMENT WILD HYBRID (*F.* X *BOHEMICA*)	BURIED TREATMENT *F. JAPONICA*	WATER TREATMENT WILD HYBRID (*F.* X *BOHEMICA*)	WATER TREATMENT *F. JAPONICA*
Days to emergence	6	6	6	6
Days to 50% regeneration	13*	6	6*	6
% regeneration by harvest	41	94	43	90
Mean shoot height at harvest (mm) ±1SE	85.4±20.6^{a}	40.8±9.3^{b}	44.6±6.7^{b}	54.7±7.9^{b}

* only achieved for Lower stem segments

4.3.2 Study 2

Rhizome treatments

Following results obtained in Study 1 (Section 4.3.1), the results of Study 2 are discussed in relation to differences observed between the four types of *Fallopia* species used in this trial, namely, *F. japonica*, *F.* x *bohemica*, *F. sachalinensis* and *F. japonica* var. *compacta*. Using results obtained in these studies and in studies reported in Chapter 2, *F. japonica* is used as a 'benchmark' against which to compare the vegetative regeneration potential of the other *Fallopia* species.

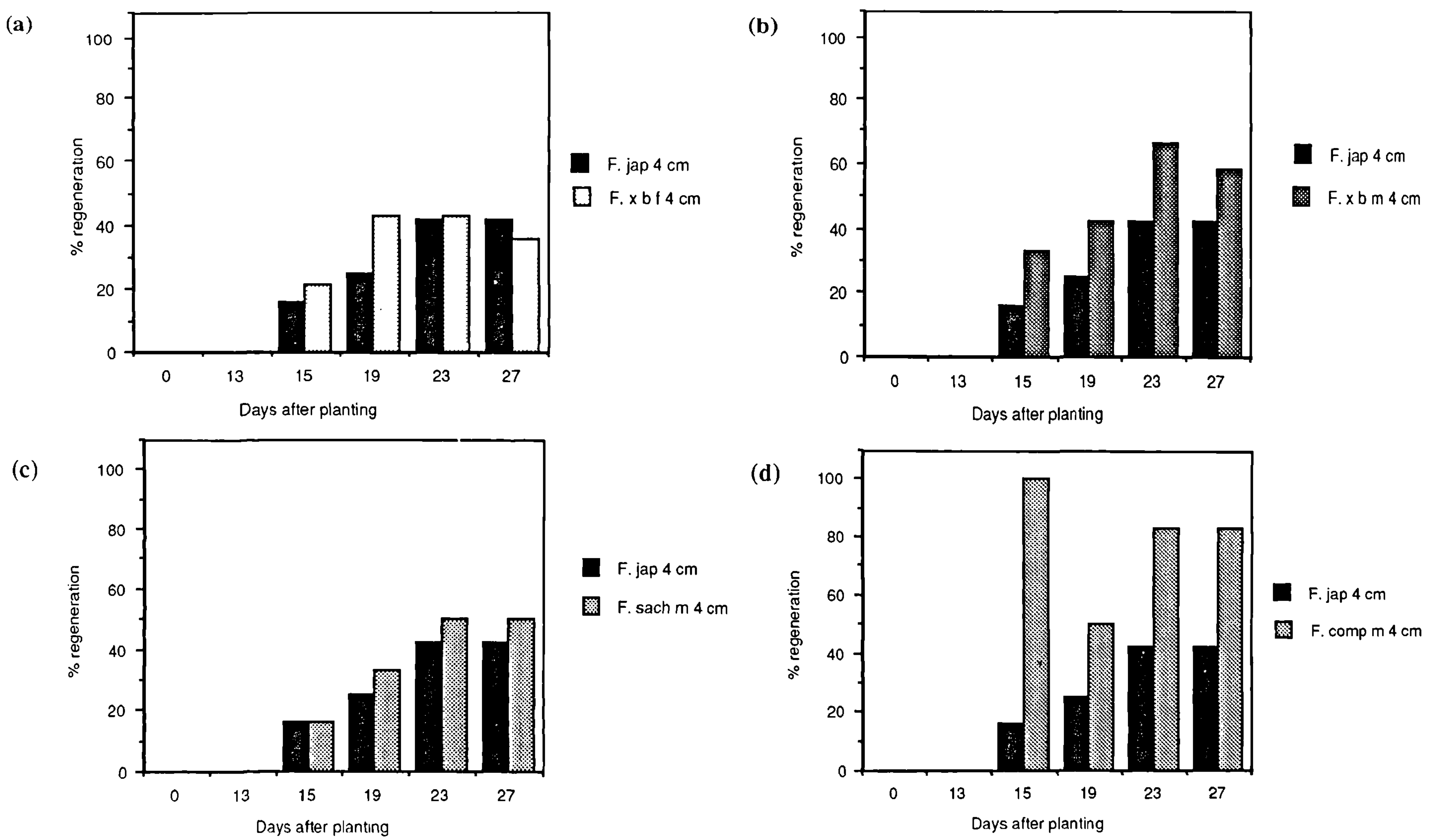


Figure 4.11 Percentage regeneration success for 4 cm rhizome fragments over the trial period of *F. japonica* compared to (a) *F.* x *bohemica* female plants, (b) *F.* x *bohemica* male plants, (c) *F. sachalinensis* plants and (d) *F. japonica* var. *compacta* plants.

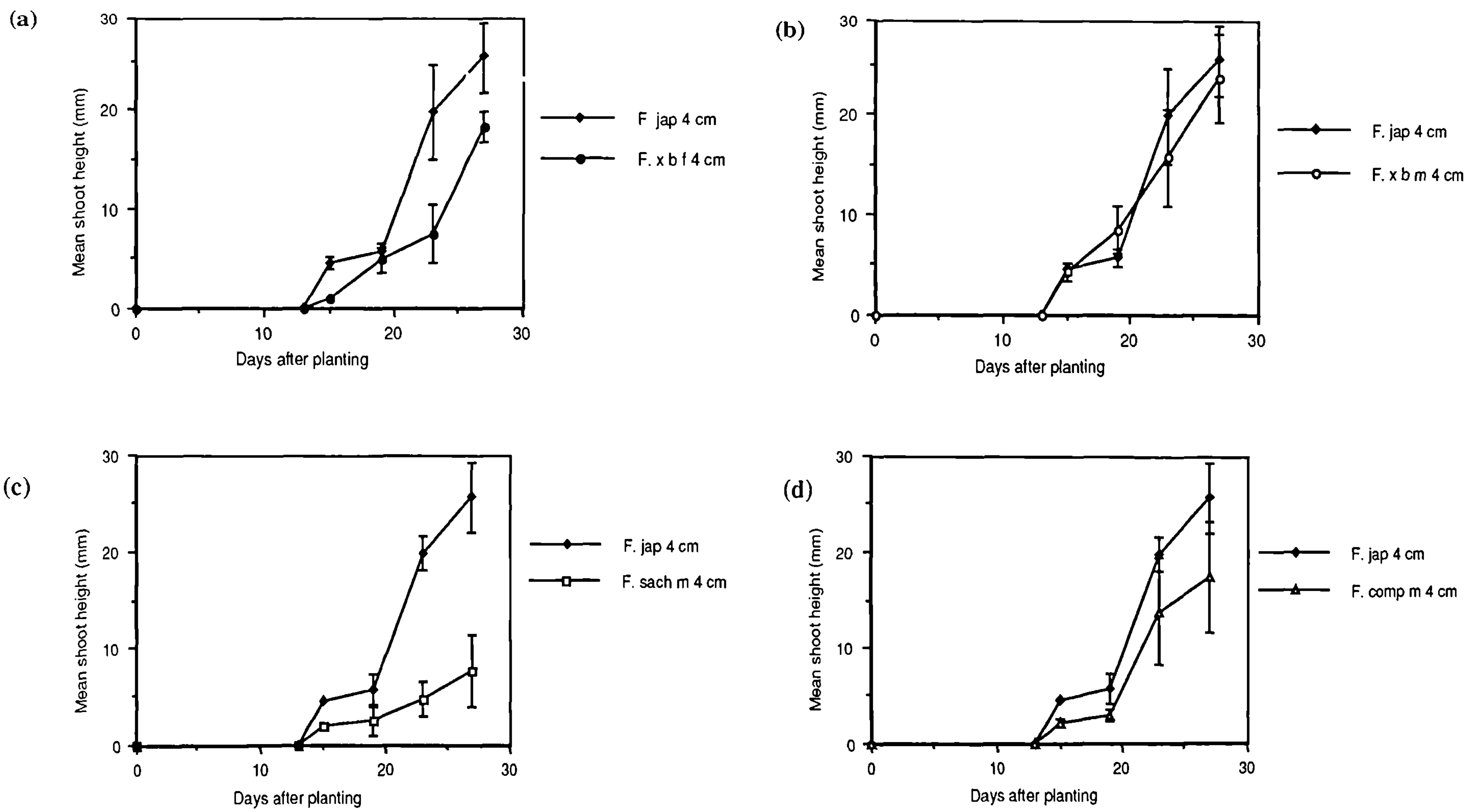


Figure 4.12 Comparison of mean shoot height produced by 4 cm length rhizome fragments of *F. japonica* and (a) *F.* x *bohemica* female plants (b) *F.* x *bohemica* male plants (c) *F. sachalinensis* plants and (d) *F. japonica* var. *compacta* plants over the trial period. Data presented are mean values ±1SE (n = 15).

Figure 4.11 a-d shows regeneration success for 4 cm rhizome fragments from hybrid plants, *F. sachalinensis* and *F. japonica* var. *compacta* in comparison to *F. japonica* throughout the trial. Rhizome fragments from male plants of *F.* x *bohemica* showed a greater initial regeneration success than fragments from female hybrids or *F. japonica* for all fragment lengths. By 19 days, both male and female hybrids had achieved a 40% regeneration rate. At 23 days after planting, male hybrid fragments had achieved a 60% regeneration success whilst both *F. japonica* and female hybrid fragments had only achieved 40%.

Figure 4.12 a-b shows a comparison of mean shoot height produced by 4 cm rhizome fragments from *F. japonica* and *F.* x *bohemica* plants over the trial period. *F. japonica* plants produced significantly taller shoots ($p < 0.05$) than female *F.* x *bohemica* plants 23 days after planting but by harvest (27 days) no significant difference was observed. Male hybrid rhizome fragments produced taller shoots than female hybrid fragments throughout the trial.

Although shoot emergence was observed at the same time, significantly taller shoots ($p < 0.05$) were produced by fragments from *F. japonica* rhizome fragments than shoots produced by either *F. japonica* var. *compacta or F. sachalinensis* fragments. This result reflects the field situation for *F. japonica* var. *compacta* which is a smaller plant but was unexpected as *F. sachalinensis* is a considerably taller plant in the field. A comparison of shoot height for 4 cm fragments is shown in Figure 4.12c.

A summary of results for the rhizome study is shown in Table 4.8. Pooling data for rhizome length allowed a comparison to be made between the various types of *Fallopia* species. *F. sachalinensis* rhizome material produced significantly smaller shoots than all other species. *F. japonica* rhizome material in this study was not as successful in regenerating as in previous studies, not reaching a 50% regeneration success rate within the trial period. This could have been due to the source of the material. All plant types used in this study, including *F. japonica,* were collected from Buckingham Palace Gardens. Previous studies on *F. japonica* (this Chapter and Chapter 2) used material from the Snell's Nook Lane location. *F. sachalinensis* and *F.* var. *compacta* 1 cm rhizome fragments and female *F.* x *bohemica* 1 and 4 cm fragments did not achieve 50% regeneration success during this trial.

Table 4.8 Summary of results from rhizome treatments. Data presented are pooled for fragment length, where appropriate range and mean values are given. Values followed by the same letter are not significantly different at the 95% significance level using Fischer's protected least significant difference test. (*F. SACH.* = *F. sachalinensis*)

CHARACTERISTIC	RHIZOME TREATMENT				
	HYBRID (*F.* X *BOHEMICA*)		*F. JAPONICA*	*F. SACH.*	*F. JAPONICA* VAR. *COMP.*
	MALE	FEMALE			
Days to emergence	15	15	15	15	15*
Days to 50% regeneration	23	-	-	15*	15*
% regeneration by harvest	40-83	18 65	33-50	50-100	100*
Mean shoot height at harvest (mm)	10.8^{a}	10.4^{a}	20.2^{a}	4.7^{b}	13.8^{a}
±1SE	±3.4	±3.8	±3.5	±1.8	±5.5

* achieved by 4 cm fragments only

\- not achieved within the trial period

Stem treatment

Percentage regeneration success from stem segments for the various *Fallopia* species are shown in Figures 4.13 a-d. For *F. japonica* and *F. sachalinensis* a 50% regeneration rate was only achieved at the end of the trial (28 days) whereas this was achieved for male and female *F.* x *bohemica* stems by 24 days (Figure 4.13a and 13b). Initially, higher regeneration rates were observed for both *F.* x *bohemica* and *F. sachalinensis* (Figure 4.13c) than for *F. japonica* but by 20 days, all had achieved a 40% regeneration success. *F. japonica* var. *compacta* failed to achieve greater than 15% regeneration success throughout the trial (Figure 4.13d).

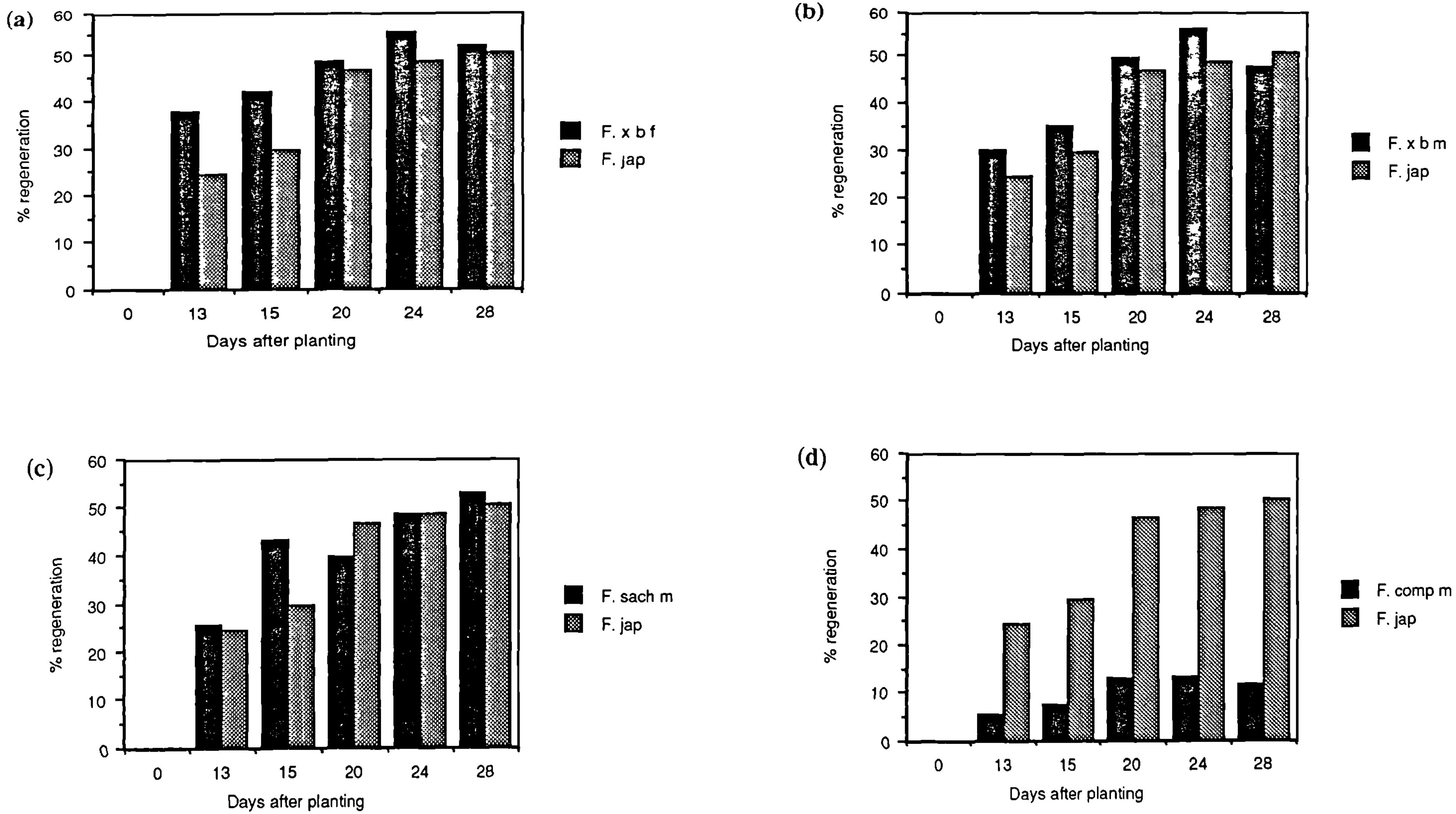


Figure 4.13 Comparison of percentage shoot regeneration from *F. japonica* and (a) *F.* x *bohemica* female (b) *F.* x *bohemica* male stems (c) *F. sachalinensis* male stems and (d) *F. japonica* var. *compacta* male stems. Data presented are pooled for segment and node.

By harvest, percentage regeneration from *F.* x *bohemica* (male and female) stems was slightly higher than that for *F. japonica* and *F. sachalinensis* and all were significantly higher than for *F. japonica* var. *compacta* which failed to achieve a 50% regeneration success rate (Figure 4.14) .

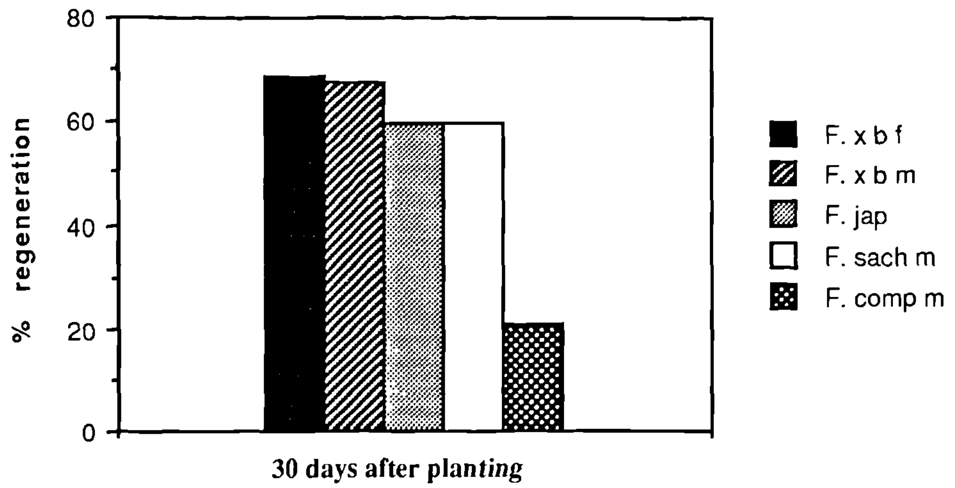


Figure 4.14 Percentage regeneration of stem segments at harvest. Data presented are pooled for segment and node (n = 45). Key: F. x b f = *F.* x *bohemica* female plants; F. x b m = *F.* x *bohemica* male plants; F. jap = *F. japonica*; F. sach m = *F. sachalinensis* male plants; F. comp m = *F. japonica* var. *compacta* male plants.

Comparisons of shoot height achieved throughout the trial are shown in Figures 4.15 a-d. *F. sachalinensis* initially showed a slightly higher growth rate than *F. japonica* but this was not significant (Figure 4.15a). *F. japonica* showed a significantly higher growth rate than *F. japonica* var. *compacta* initially but this trend was reversed after 23 days, resulting in no significant differences in shoot height at the end of the trial (Figure 4.15b). Shoot height achieved by *F.* x *bohemica* stems was significantly greater ($p < 0.05$) than that for *F. japonica* by the end of the trial with female *F.* x *bohemica* plants attaining the greatest height (Figures 4.15 c-d).

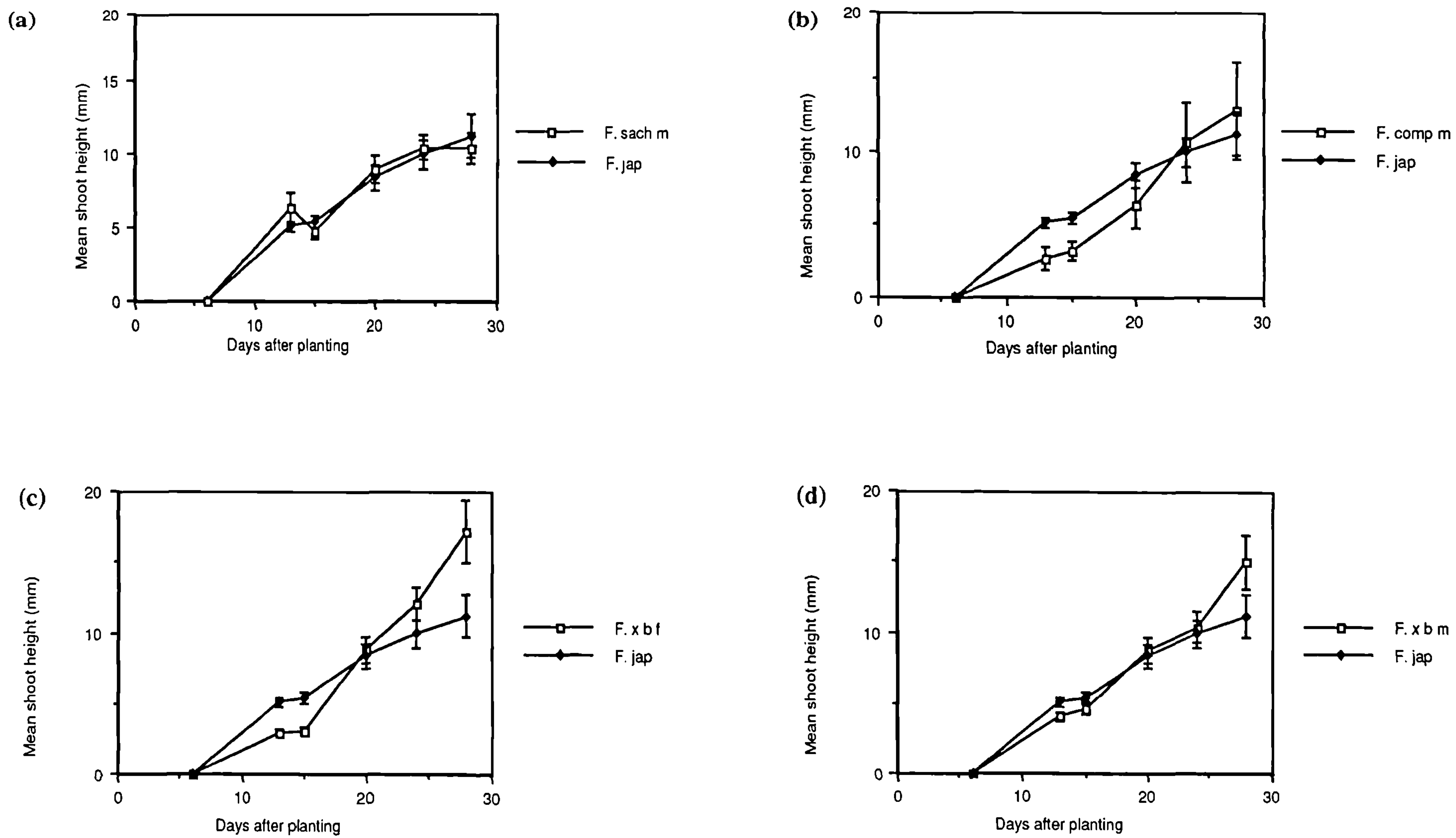


Figure 4.15 Shoot height achieved by stems subjected to water treatment for *F. japonica* and (a) *F. sachalinensis* plants, (b) *F. japonica* var. *compacta* plants (c) *F.* x *bohemica* female plants and (d) *F.* x *bohemica* male plants throughout the trial. Data presented mean values ±1SE and are pooled for stem segment and node

By harvest, the greatest shoot height was achieved by *F.* x *bohemica* female plants (Figure 4.16). This was not significantly different to that achieved by male hybrid, *F.* x *bohemica* but was significantly greater ($p < 0.05$) than that achieved by *F. japonica*, *F. sachalinensis* and *F. japonica* var. *compacta*.

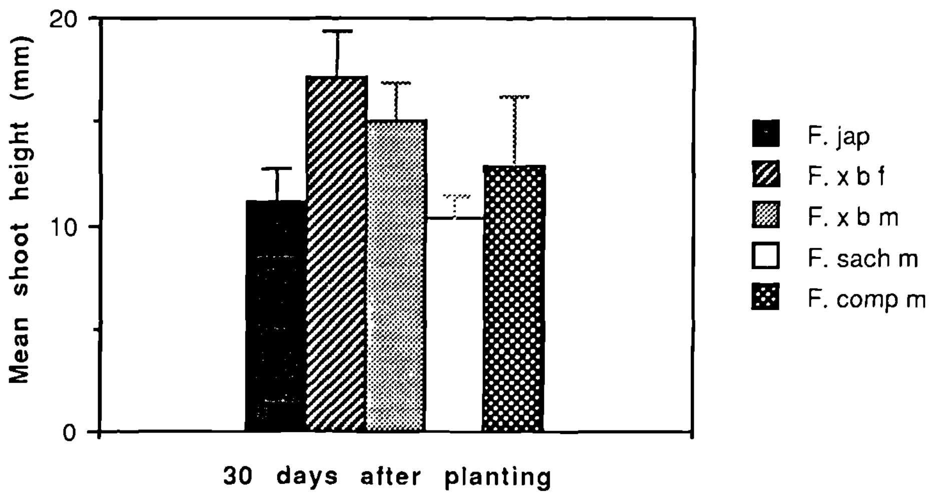


Figure 4.16 Height achieved by shoots at harvest from regeneration of cut stems subjected to water treatment. Data are presented as mean values ±1 SE and are pooled for stem segment and node. Key: F. x bf = *F.* x *bohemica* female plants; F. x bm = *F.* x *bohemica* male plants; F. jap = *F. japonica*; F. sach m = *F. sachalinensis* male plants; F. comp male = *F. japonica* var. *compacta*.

Significant differences were observed between shoot height produced by stem segments for *F. japonica* and male and female *F.* x *bohemica* plants with lower and middle stems segments producing significantly ($p < 0.05$) taller shoots than those produced by upper stem segments. No significant differences were observed between height of shoots produced by any segments for *F. sachalinensis* or *F. japonica* var. *compacta* stems. A summary of results for stem treatments is shown in Table 4.9.

Table 4.9 Summary of results from stem segment treatments. Data presented are pooled for segment and node, where appropriate range and mean values are given. Values followed by the same letter are not significantly different at the 95% significance level using Fischer's protected least significant difference test.
(*F. SACH.* = *F. sachalinensis*)

CHARACTERISTIC	WATER TREATMENT				
	HYBRID (*F.* X *BOHEMICA*) MALE	FEMALE	*F. JAPONICA*	*F. SACH.*	*F. JAPONICA* VAR. *COMP.*
Days to emergence	6	6	6	6	6
Days to 50% regeneration	13*	17	20	17	-
% regeneration by harvest	50-77	39-90	43-76	40-80	3-43
Mean shoot height at harvest (mm)	15.0^{a}	17.2^{a}	11.2^{b}	8.2^{b}	12.8^{b}
±1SE	±1.9	±2.3	±1.5	±0.6	±3.4

4.4 DISCUSSION

The results of these trials on hybrid and parental *Fallopia* species rhizome and stem material have identified important differences in the success rates of regeneration, the time required to regenerate and the production of shoot material. In these studies, a comparison of wild and artificial *F.* x *bohemica* plant material shows that wild hybrid material exhibited a higher percentage regeneration rate for all fragment lengths over the trial period than either the artificial hybrid or *F. japonica.* Shoots emerged 6 days after planting and the regeneration success was maintained throughout. Of the 60 wild hybrid rhizome fragments planted, only one 1 cm fragment failed to regenerate during the trial indicating that the minimum weight of the smallest fragment of hybrid material required to produce a shoot was 0.89 g. This is comparable with the studies carried out in Chapter 2 on *F. japonica* and earlier greenhouse trials by Brock and Wade (1992) who gave 0.7 g as the minimum weight of *F. japonica* rhizome required to produce shoots. These results suggest that hybrid rhizome material exhibits a comparable regeneration potential to that of *F. japonica* in terms of minimum size of propagule required to produce shoots. This high regeneration success rate for hybrid rhizomes suggests that *F.* x *bohemica* and *F. japonica* exhibit a similar high potential for vegetative reproduction.

Artificial hybrid 4 cm rhizome fragments required 15 days to achieve a 50 % regeneration success, 2 and 8 cm fragments did not achieve this until 20 days after planting and 1 cm fragments not at all. These results confirm observations in Chapter 2 on *F. japonica* where 4 cm rhizome lengths gave optimum regeneration success. The wild hybrid material achieved a 50% regeneration rate for all but 1 cm fragments only 6 days after planting. Wild hybrid material was therefore more successful not only in terms of its regeneration success but also in terms of the length of time required for shoot emergence. When compared to *F. japonica* rhizome fragments in this and earlier studies (Chapter 2), which required from 13 to 24 days after planting to achieve 50% regeneration success (Figure 2.2), the combination of time taken to produce shoots and overall success rate means that the hybrid rhizomes are very competitive in terms of their regenerative capacity. Shoot production was initiated earlier and shoot height produced was greater for wild hybrid rhizomes than for artificial hybrids. Number of leaves produced was also greater in wild hybrids early in the trial indicating rapid establishment.

It is possible that the differences observed between artificial and wild hybrid material was due to the age and maturity of wild plants. The wild material covered a large area of open road verge and was well established. The artificially created hybrids had been established for at least 5 years but were container grown (Bailey, pers comm.). The extension of rhizomes from mature plants has been recorded as spreading at least 7 m away from a parent plant (Palmer, 1990; Beerling *et al.*, 1994) and it is possible that the wild hybrid plants had access to a greater resource in terms of nutrient and water availability through a more extensive rhizome system. An increase in rhizome resources in this material could account for the differential growth rate observed in wild hybrids. However, the wild hybrid source material was from male-fertile plants whereas the artificial hybrid material was from female (male-sterile) plants. Differences observed in the second trials confirm that rhizome material from male-fertile hybrids regenerates more rapidly than that from female (male-sterile) hybrid plants.

Hybrid plants also produced significantly taller shoots than *F. japonica* in these trials which confirms that rhizome material from hybrid plants has the potential to be as invasive as rhizome material from *F. japonica*. The results of this study underline the importance of vegetative regeneration in the dispersal and spread of the hybrid to new sites. Minimising the risk of transportation of fragmented hybrid rhizome material will therefore be an important factor in the future management of these plants.

Results of the stem regeneration study indicate that hybrid stem material is not as successful in terms of regeneration as *F. japonica*. Hybrid stems subjected to water and buried treatments produced shoots after the same length of time as *F. japonica* (6 days) but had lower regeneration rates. A 50% regeneration rate was not achieved for hybrid stems subjected to either water or buried treatments in the first trial. *F. japonica* stems subjected to water treatment achieved high regeneration rates early in the trial (80% at 6 days) and *F. japonica* stems subjected to buried treatment achieved higher regeneration rates than either of the hybrid treatments. Although middle stem segments of hybrids in the buried treatment produced the tallest shoots initially, shoots produced by *F. japonica* lower segments were significantly taller than those produced by hybrid stems in both water and buried treatments by the end of the trial.

The results of the stem regeneration trials contrast with the results from the rhizome trials. Hybrid rhizomes have a greater invasive potential than *F. japonica* whereas the success of stem regeneration is not as great. This is notable particularly in relation to dispersal of the plants in riparian areas. Chapter 2 identified the potential for floating cut stems of *F. japonica* to form new plants and a comparison of shoot height produced by rhizome fragments and cut stems showed no difference in shoot height once regeneration had been achieved. In this study, shoot regeneration from hybrid stem material is significantly lower than that for *F. japonica* stem material subjected to the same environmental conditions. It is interesting to note that the majority of hybrid locations identified to date are situated on road verges and waste ground rather than on river and stream banks (Chapter 3). The results obtained in these trials suggest that cut stems of hybrid plants do carry a risk of regeneration if buried or washed into watercourses following management techniques such as mowing and cutting. The potential for regeneration from rhizome material however is far greater.

The results of these studies raise two important questions in relation to future management of this group of species:

What are the differences in the regeneration potential of rhizomes and stems for male and female hybrid plants?
How do the regeneration rates for *F.* x *bohemica* stem and rhizome fragments compare with rates for parental material?

Rhizome fragments from male-fertile *F.* x *bohemica* plants achieved a greater percentage regeneration rate than rhizome fragments from female plants. This was observed for all rhizome fragment lengths. Date of shoot emergence coincided (6 days) but the rate of increase in shoot height was greater for male-fertile hybrid plants than for female plants throughout the trial. The differences were significant initially but by harvest (28 days) no significant difference in shoot height was observed.

In the stem regeneration trial, female hybrid stems initially achieved a greater percentage regeneration than male hybrid stems however, by 25 days, this trend had reversed. Shoot height was also greater for female hybrids than for male plant stems but differences were only significant early in the trial. Both hybrid forms produced taller shoots than *F. japonica*. Using the results of the second study, a comparison of regeneration rates and shoot production from rhizome and stem material of *F.* x *bohemica* and its potential parents *F. japonica*, *F. sachalinensis* and *F. japonica* var. *compacta* can be made.

Figure 4.17 shows a comparison of the time required to achieve a 50% regeneration rate for 4 cm fragments of planted rhizome material from the various *Fallopia* species in these trials. The most rapid regeneration rate was observed for the wild male plants of *F.* x *bohemica* collected from the road verge site in study one. The time requirement was notably shorter than that observed for *F. japonica* in these or earlier trials (Chapter 2). This observation indicates a large invasive potential for hybrid material especially *via* rhizome fragments. Rapid regeneration rates mean that in a short time, establishment of plants at new sites can occur following importation of rhizome material. Interestingly, although regeneration times for female hybrid plants were not as rapid, they are nonetheless comparable to those for *F. japonica*. Hybrid rhizome material is therefore at least as potentially invasive as its female parent *F. japonica*.

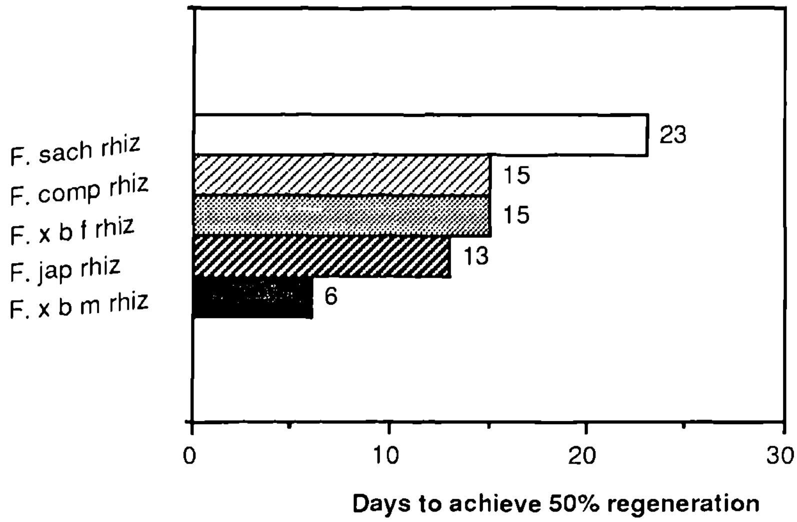


Figure 4.17 Comparison of time required to achieve a 50% regeneration success rate for planted rhizomes (4 cm fragments). Data presented are pooled mean values from the two trials conducted in this study. Key: F. sach = *F. sachalinensis*; F. comp = *F. japonica* var. *compacta*; F. x b f = *F.* x *bohemica* female plants; F. jap = *F. japonica*; F. x b m = *F.* x *bohemica* male plants.

F. sachalinensis shows a significantly lower rate of rhizome regeneration when compared to *F. japonica* and significantly smaller shoots. Although *F. sachalinensis* exists in the field as a much taller plant than *F. japonica*, achieving a height of approx. 5 m, significantly taller shoots from rhizome fragments were not observed in these trials. The reason for this is not clear, further work on the growth rates of these related species is required. *F. japonica* var. *compacta* achieved comparable rhizome regeneration rates but shoot height was not as great as for *F. japonica*. *F. japonica* var. *compacta* is a small plant, growing only to 1 m in height and is not as widespread in the British Isles as the other *Fallopia* species (Conolly, 1977). The results of these trials reflect the situation found in the wild where neither *F. sachalinensis* or *F. japonica* var. *compacta* are as invasive as *F. japonica*. However, both *F. japonica* var. *compacta* and *F. sachalinensis* regenerate successfully from rhizome material and this aspect should be considered when managing these species.

In terms of stem regeneration rates, *F. japonica* stems subjected to a water sun treatment showed the most rapid regeneration success (Figure 4.18). Stem material from hybrid plants and *F. sachalinensis* required more time to achieve a 50%

regeneration success. Interestingly, both male and female hybrid plants were comparable to *F. sachalinensis* in the stem regeneration trials. *F. japonica* var. *compacta* failed to achieve a 50% regeneration success throughout the trial. In terms of shoot height, only *F.* x *bohemica* stems produced taller shoots than *F. japonica.*

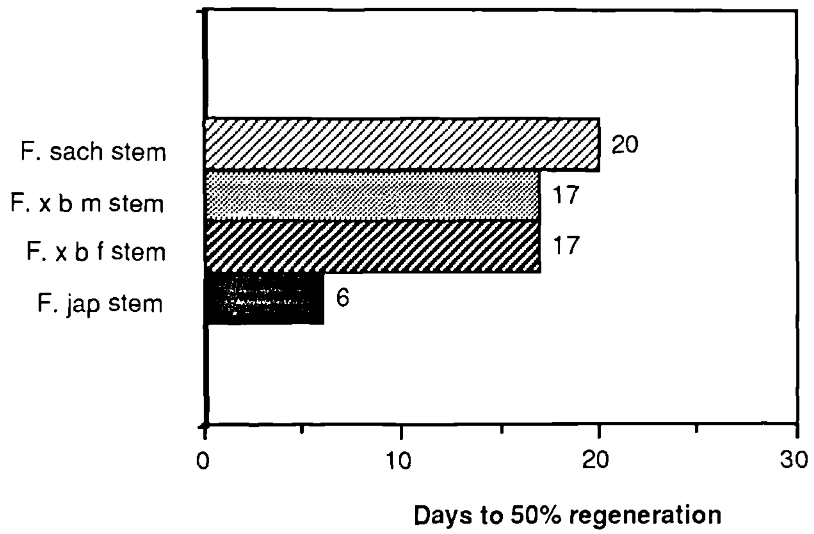


Figure 4.18 Comparison of time required to achieve a 50% regeneration success rate for stems subjected to water sun treatments. Key: F. sach = *F. sachalinensis*; F. x b m = *F.* x *bohemica* male plants; F. x b f = *F.* x *bohemica* female plants; F. jap = *F. japonica.*

The results obtained in these trials suggest a trend towards a higher invasive potential for rhizomes from male-fertile hybrid plants compared to that of female hybrids with male-fertile source material generating shoots in half the time required for male-sterile (female) plants. The potential for regeneration following transportation of fragments of rhizomes in soil could result in a greater expansion of male plants than female plants by this means. An increase in the potential source of pollen from these plants for further hybridisation and back-crossing with *F. japonica* could lead to greater fertile seed set. Further work will be required to investigate the contribution to which sexual reproduction may become a major means of dispersal and spread of these species in the future.

It is clear from the results of these studies that the vegetative regeneration potential of *F.* x *bohemica* is comparable with that of *F. japonica*, particularly in relation to the potential spread of hybrid plants by rhizome fragments. The implications of this finding on potential control measures are two-fold. Firstly, there is potential for an increase in male-fertile plants in the environment which could in future lead to successful sexual reproduction and dispersal by seed Secondly, vegetative dispersal will inevitably lead to an increase in the hybrid population throughout the British Isles through anthropogenic and natural disturbance as has been the case with *F. japonica*. In contrast to *F. japonica* however, *F.* x *bohemica* is genetically more diverse, existing at two ploidy levels (chromosome numbers 2n = 44 and 2n = 66) and in both its male-fertile and female forms. This feature of hybrid populations has potential implications for any proposed biological control programme. Whereas clonal plants such as *F. japonica* make good candidates for biological control due to lack of genetic variability and therefore exhibit uniform susceptibility to control organisms, hybrid populations with a more diverse genetic constitution may display some degree of genetic resistance. Any future biological control programme should therefore take into account the genetic variation within hybrid populations and ensure that host specificity trials are conducted on the wider range of *Fallopia* species identified in this chapter.

Given that their vegetative regeneration rates are comparable with that of *F. japonica* the potential expansion of hybrid populations is extensive. Further monitoring will be necessary to assess their expansion in the British Isles in order to prevent a secondary invasion of *Fallopia* hybrids.

4.5 CONCLUSIONS

- Wild hybrid rhizome fragments (*F.* x *bohemica*) achieved higher percentage regeneration rates, more rapid shoot emergence and produced leaves earlier than artificial hybrid or *F. japonica* rhizome material.
- Hybrid stem segments subjected to buried treatments achieved a higher regeneration rate than those subjected to water treatment.
- *F. japonica* stem segments achieved higher and more rapid regeneration rates for both buried and water treatments than hybrid stems.
- Rhizome fragments from male *F.* x *bohemica* hybrids achieved a greater percentage regeneration success than those of female hybrids or *F. japonica*.

- Female hybrid stems showed a greater percentage of shoots than male hybrid stems initially. Shoot height achieved by female hybrid stems was greater than that produced by all other types.
- Height of shoots produced from rhizome fragments was greater for *F. japonica* than for *F.* x *bohemica*, *F. japonica* var. *compacta* or *F. sachalinensis* at harvest.
- Future management will need to consider the high regeneration potential of each of these species

5.0 CONTROL OF *FALLOPIA JAPONICA* USING A COMBINATION OF TREATMENTS

5.1 INTRODUCTION

5.1.1 Background

Fallopia japonica has gained something of a reputation with land managers as a plant which is resistant to control measures. Proximity to water courses, the presence of other species of nature conservation value and not least, the structure of the plant itself have proved to be major factors inhibiting the effective control of this vigorously invasive plant (Beerling, 1990b; Child *et al.*, 1998). The extent and regeneration capacity of underground rhizomes is so great, that mechanical measures such as cutting or mowing, normally used effectively for other nuisance species to reduce above ground vigour, are not effective against *F. japonica*. The large underground rhizome system, which may extend up to 7 m laterally and to a depth of 2 m vertically from the parent plant (Richards, Moorehead and Laing Ltd., 1990) must be a major limitation to the effective and rapid control of *F. japonica*.

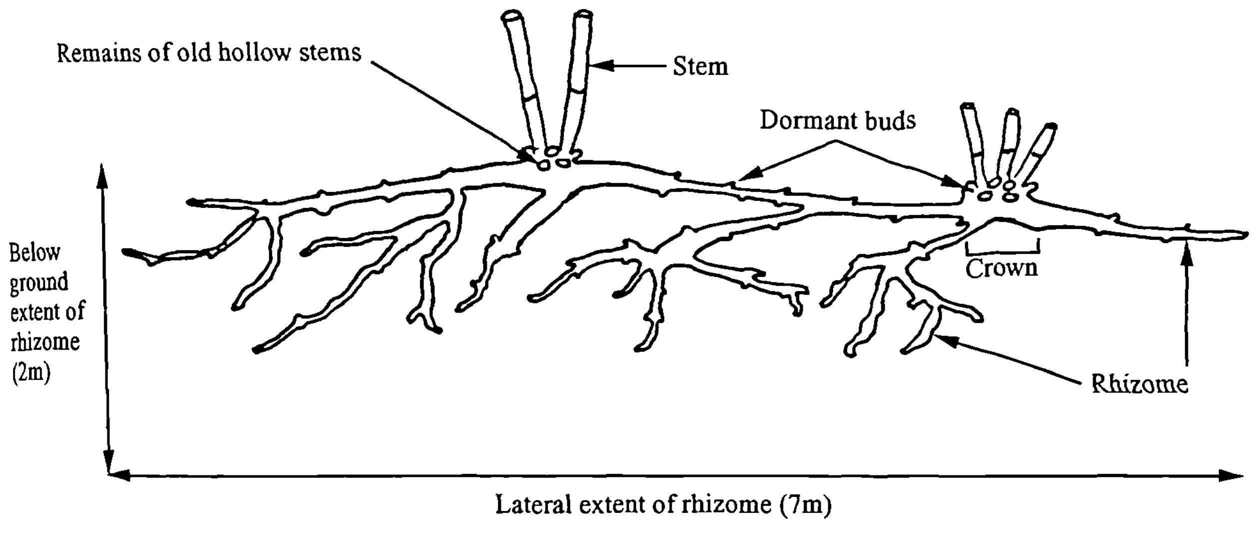


Figure 5.1 Diagrammatic representation of *F. japonica* rhizome system showing formation of crowns and dormant buds

The rhizome system provides not only a nutrient store and over wintering organ but is also the site of new bud initiation. Buds begin to form on rhizomes at the base of stems and at nodes along the rhizomes towards the end of the growing season, remaining dormant over the winter and allowing for rapid shoot development in spring (Figure 5.1). No data are available on the length of time for which buds remain viable. The high regeneration rate of *F. japonica* from 1 cm rhizome fragments (Chapter 2) weighing as little as 0.7 g (Brock and Wade, 1992; Brock *et al.*, 1995) indicates the importance of the rhizome system in the survival of the plant and in its means of dispersal. An estimate of the underground biomass in just the upper 25 cm of soil is given by Brock (1994) as 14,000 kg ha^{-1} dry weight representing a considerable mass of plant material. Consequently, when deciding on a control method for *F. japonica*, effective treatment of the rhizome system must be of prime consideration. In terms of a single method approach, a translocated herbicide which targets the rhizome system therefore offers the most successful control method.

There is strict regulation governing the use of herbicides in the British Isles. Any method of chemical control has to be carried out in a manner which ensures environmental and personal safety and which satisfies the various regulations governing herbicide use. Legislation includes: The Health and Safety at Work Act 1974; Control of Pollution Act, 1974; The Food and Environmental Protection Act, 1985; Control of Pesticides Regulations 1986 and The Control of Substances Hazardous to Health Regulations (COSHH) 1994 (Ministry of Agriculture, Fisheries and Food, 1995; Welsh Development Agency, 1998a). The Control of Pesticides Regulations fall under the Food and Environmental Protection Act (FEPA) and cover the use of herbicides. Approval for the use of particular herbicides is a legal requirement and it is an offence to use non-approved products or to use approved products in a manner which does not comply with specific conditions of approval. These conditions are specified on product labels. The FEPA regulations replace the non-statutory Pesticides Safety Precautions Scheme (PSPS) but continue to grant clearance for those products which were PSPS approved for use near watercourses. Only a restricted number of herbicides are permitted for use in these situations. Under this legislation, two herbicides approved for use in or near water have been shown to be effective against *F. japonica*. These are glyphosate and 2,4-D amine (Roblin, 1988; Beerling, 1990b; de Waal, 1995). Both are non-persistent translocated herbicides and whereas 2,4-D amine is selective for broad-leaved species, glyphosate is non-selective but is often favoured for its low toxicity (Stensones and Garnett, 1994).

Other translocated herbicides which have been shown in trials to be effective against *F. japonica* are picloram, triclopyr (Harper and Stott, 1966; Scott and Marrs, 1984) and imazapyr (Welsh Development Agency, 1998a). However, none of these are approved for use near water under the FEPA regulations and all are approved only for non-crop areas. All three of these herbicides are persistent in the soil following application, preventing the replacement of vegetation (Welsh Development Agency, 1998a). The minimum delay period for replanting broad-leaved species following application of triclopyr is 3 months and for picloram, 2 years (Ivens, 1993). The persistence of imazapyr is dependent on dose and environmental conditions, although imazapyr is recommended for use on sites where long term total vegetation control is required such as railway lines, industrial sites and paved areas (Cyanamid, no date). Although picloram is selective for broad leaved species, there is a risk of migration through soil, especially on sloping ground with a risk of causing damage to non-target plants outside the treatment site. The use of products containing picloram is therefore restricted to sites where soil water migration patterns are well established and there is no possibility of the herbicide leaching into watercourses or affecting non-target plants. Both triclopyr and imazapyr are non-selective herbicides and are therefore suitable for application to areas where total vegetation control is required such as paving, hard surfaces and industrial sites. Herbicides are generally applied as a foliar spray during the growing season and should be used only in accordance with manufacturers instructions. Alternative methods of application such as the use of a weed-wiper, weed glove or cut stem treatments may also be employed if the manufacturers instructions permit.

Beerling (1990b) achieved significant reduction in plant biomass and leaf area ratio after one season using 2,4-D amine but no follow up monitoring was undertaken to assess long term control. Harper and Stott (1966) carried out field trials using a range of herbicides and achieved good control of *F. japonica* using picloram applied as a foliar spray. Scott and Marrs (1984) also came to the conclusion that picloram was most effective for control of the plant but recommended that it should only be used on sites without run-off hazard to agriculture or wildlife. Difficulties were experienced by both groups of researchers in physically gaining access to full growth *F. japonica* plants and recommended that plants should either be sprayed early in the season when the plant is in the active period of plant extension or that stems should be cut to debilitate the plant with a follow up spray when the re-growth has reached a height of 1.0 - 1.5 m. The use of specialised applicators such as the telescopic lance (Barrett, 1990; Barrett and Newman, 1991) could be employed particularly for treating the plant in areas such as steep embankments where access for cutting and spraying with conventional equipment is difficult. De Waal (1995) achieved a 95% kill after two applications of glyphosate but noted that plants treated with a telescopic lance took longer to show treatment effects than those treated *via* a conventional lance. These results may be attributable to differences in spray pressure between the two applicators which may have altered the delivery rate. Roblin (1988) reported that two applications of glyphosate a year over several years would be required to effect complete control. It is clear then, that *F. japonica* is susceptible to herbicide treatment but that it is necessary to continue the use of control measures for a number of years before eradication is achieved.

Fallopia japonica has become a particular problem in the urban environment, especially on waste industrial sites (Child *et al.*, 1992; Child and de Waal, 1997; Child and Wade, 1997; Child *et al.*, 1998). Disturbance of established *F. japonica* plants on infested sites subject to redevelopment works such as building or highway improvements, can spread the plant effectively over large areas of the site due to fragmentation and subsequent burial of rhizomes which leads to enhanced rates of regeneration. On such sites designated for redevelopment, treatment of the plant is necessary prior to work commencing (Welsh Development Agency, 1998a) in order to avoid subsequent damage to buildings, paving and landscaping by *F. japonica* growth. A rapid and cost effective method of control is therefore required for such sites.

The Welsh Development Agency (1998a) has produced comprehensive guidelines for landscape contractors on procedures to be adopted when *F. japonica* is present on sites designated for redevelopment. There are three possible options:

1. To treat the plants *in situ* with an approved herbicide before development work commences
2. To excavate plants along with the surrounding soil to a depth of at least 2 m and to a diameter of 7 m from live plants
   and either

(i) spread the soil containing *F. japonica* over a designated area of the site for treatment with an approved herbicide whilst development work continues elsewhere on the site

or

(ii) bury the soil containing *F. japonica* in a trench on site, compact and cover with at least 2 m of non-compacted soil

3. Excavate plants and surrounding soil as above and cart away to a licensed landfill site.

The disposal of *F. japonica* stems and rhizomes in the UK is subject to Environmental Protection (Duty of Care) Regulations (Department of the Environment, 1991) and as such must be disposed of at a licensed landfill site (Ministry of Agriculture, Fisheries and Food, 1995; Welsh Development Agency, 1998a; 1998b).

Where a site has not been available for pre-treatment of *F. japonica* and where no space is available to retain and treat contaminated soils on site, option 3 is employed. This involves removal from the site of top soil containing plant fragments to a depth of at least 2 m and transporting the spoil for burial at a licensed landfill site. The cost of this extreme measure is very high in terms of transportation costs, landfill charges and landfill tax and is wasteful in terms of land resources. A recent estimate of the cost of removing 2,730 m^3 of soil contaminated with *F. japonica* rhizomes from a redevelopment site in Cardiff, South Wales and subsequent disposal to landfill, was in the region of £ 0.5 million (pers. comm. Kajima Engineering, Cardiff).

Redevelopment of urban sites is often delayed when *F. japonica* is growing on site. Financial appraisal of redevelopment sites includes an element for the length of time during which the land remains unused before development, known as the 'waiting time', where investment costs, in terms of land purchase cost and interest payments (the Total Finance Costs), accumulate. If this 'waiting time' could be cut by rapid treatment of *F. japonica*, the costs associated with the pre-treatment of sites would fall significantly. In cases where land does not become available to a potential redeveloper until building work is due to commence, suitable areas may be found on site for transfer of infested soils for later treatment. However, on small sites and those where compulsory purchase orders necessitate the acquisition of a minimum land area such as highway improvements, where no space is available for transfer of infested soil, rapid treatment on site is required to avoid the excessive costs of removal of infested material to landfill.

5.1.2 Aims and objectives

The study reported in this chapter was undertaken in order to explore a potential cost effective and rapid treatment for the control of *F. japonica* which could be employed specifically on urban redevelopment sites (Child *et al.*, 1998). The rationale behind the study uses the information gained from Chapter 2 which identified a high regeneration potential for small fragments of rhizome material. The hypothesis underlying this investigation is that digging a site contaminated with *F. japonica* would thoroughly fragment the rhizome system, resulting in stimulation of plant growth from rhizome fragments. Three questions arise from this hypothesis:

(i) Would an increase in growth resulting from disturbance make the plant more or less susceptible to control by a translocated herbicide?

(ii) What would be the impact of a combination of treatments on the time required to achieve an acceptable level of control? (95% kill as determined by the Welsh Development Agency, 1998a)

(iii) What would be the implications of the treatments in terms of costs?

A specific objective was to investigate:

- the impact of three treatments (digging, spraying and a combined treatment of digging and spraying) on stem density, plant height, stem diameter and leaf number of fully developed plants of *F. japonica*

On the basis of these findings it was intended that results be used to:

- identify the time period necessary to achieve a good level of control for each of the treatments
- undertake an assessment of costs relating to the treatment of *F. japonica* on land awaiting redevelopment using the most effective control strategy

Digging with an excavator was selected in preference to deep cultivation with tynes in order to thoroughly fragment the full below-ground extent of the rhizome system. In the current study, rhizomes were observed to a depth of 0.5 m, in other situations, rhizomes may penetrate to a depth of 2 m (Figure 5.1). This requires a method which ensures deep excavation rather than surface cultivation in order to achieve fragmentation of all below-ground material.

5.2 METHODS

5.2.1 Site description

The treatment site selected for trials was an area of waste industrial land infested with *F. japonica* at Mill Meads, Stratford, East London, National Grid reference TQ 385830. The site, privately owned by Thames Water Authority, was identified as a suitable site for the trial as it was undergoing major redevelopment works and could be secured for the period of the trial without disturbance. The site is adjacent to Abbey Creek at its confluence with the Channelsea River, a tributary of the River Thames.

5.2.2 Experimental Design

An area of approximately 1,100 m^2 of monoculture *F. japonica* was divided into six treatment plots (Figure 5.2) within which, central to each plot, three 1 m^2 replicate sub-plots were used for monitoring. Plots were of sufficient width (minimum 12 m) to ensure that edge effects (such as rhizome extension from adjacent plots) were not encountered in monitoring quadrats.

Treatments were allocated to plots to be carried out initially over a two year period (1993-1995). Two treatments DIGGING and SPRAYING were applied at two levels (DUG, NOT DUG and SPRAYED, NOT SPRAYED) in a fully crossed factorial design (Table 5.1).

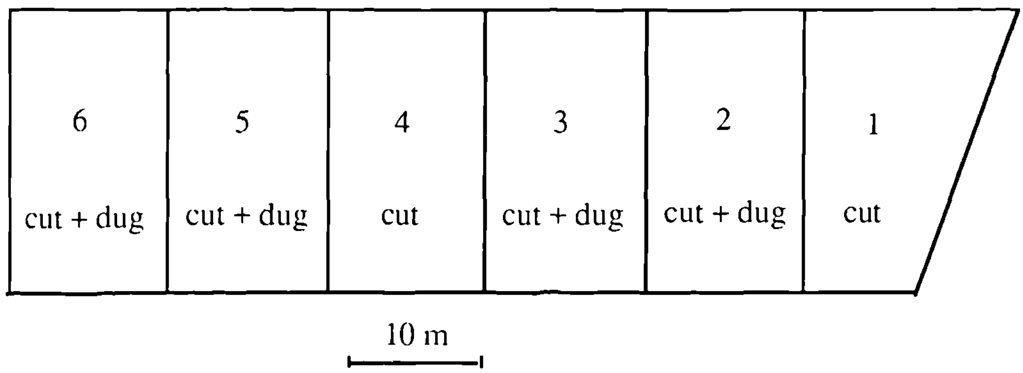


Figure 5.2 Area of trial site showing plot division and preparation treatments carried out in autumn 1993

Table 5.1 Experimental design of initial trial (1993-1995)

TREATMENT	DIGGING	
	LEVEL 1	LEVEL 2
SPRAYING LEVEL 1	dug sprayed	not dug sprayed
LEVEL 2	dug not sprayed	not dug not sprayed

Four plots were assigned to digging treatments so that these could be further separated in year three for a follow up treatment if necessary. In year three (July 1996), a follow up trial was undertaken with a further spray application to *F. japonica* plants in designated plots (Table 5.2).

Table 5.2 Design of follow up trial 1996 (in italics) superimposed on initial trial experimental design.

<table>
<tr><td rowspan="2">TREATMENT</td><td colspan="3">DIGGING</td></tr>
<tr><td colspan="2">LEVEL 1</td><td>LEVEL 2</td></tr>
<tr><td>SPRAYING
LEVEL 1</td><td colspan="2">dug
sprayed</td><td>not dug
sprayed</td></tr>
<tr><td>1996</td><td colspan="2">sprayed</td><td>sprayed</td></tr>
<tr><td>LEVEL 2</td><td colspan="2">dug
not sprayed</td><td>not dug
not sprayed</td></tr>
<tr><td>1996</td><td>not sprayed</td><td>sprayed</td><td>not sprayed</td></tr>
</table>

Strimming using a metal bladed strimmer was carried out prior to and at intervals during the trial in order to clear dead stem material and improve access to plots for treatment and monitoring. In order to negate this as a treatment effect, strimming, when carried out, was applied to all plots.

5.2.3 Site preparation and treatments

Timing of treatments is indicated in Tables 5.3 and 5.4.

Table 5.3 Timing of treatments and monitoring for initial trial

INITIAL TRIAL

PLOT	SEPT 93	OCT 93	MAY 94	MAY 94	SEPT 94	MAY 95
1	Strimming		Monitoring	Spraying	Strimming	Monitoring
2 + 3	Strimming	Digging	Monitoring	Spraying	Strimming	Monitoring
4	Strimming		Monitoring		Strimming	Monitoring
5 + 6	Strimming	Digging	Monitoring		Strimming	Monitoring

Table 5.4 Timing of treatments and monitoring for follow up trial

FOLLOW UP TRIAL

PLOT	JUNE 96	JULY 96	JULY 96	NOV 96
1	Strimming	Monitoring	Spraying	Monitoring
2 + 3	Strimming	Monitoring	Spraying	Monitoring
4	Strimming	Monitoring		Monitoring
5	Strimming	Monitoring		Monitoring
6	Strimming	Monitoring	Spraying	Monitoring

Strimming

The site was prepared in late September 1993, when dead stems of *F. japonica* over all plots were cut to a height of 200 mm using a metal bladed strimmer. At the end of the growing season in 1994, all plots were strimmed to remove dead stems to allow easy access for monitoring. Access to plots for monitoring was made difficult in June 1996 by excessive growth of both *F. japonica* and other species. All plots were therefore strimmed in June 1996 and monitoring was carried out on re-growth in July

1996. All cut material was left *in situ* to dry out on the soil surface to minimise risk of spread in transportation.

Digging
On 12 October 1993, four plots were dug by contractors using a JCB mechanical excavator with a 0.24 m^3 bucket. An area of approximately 370 m^2 was dug in 2.5 hours. Surface crowns and rhizomes were scraped from the soil surface into a pile. Soil was cultivated to a depth of 0.5 m which was determined by observation to be the maximum depth of penetration of rhizomes. Cultivated soil was thoroughly turned and replaced, spreading to re-make a level surface. Piled crowns and rhizomes were spread back over the cultivated area to restore a level surface (Figure 5.3). The site was left in this condition over the winter 1993-4.

Spraying
As the site was adjacent to water, only those herbicides approved for use near water by Ministry of Agriculture Fisheries and Food (1995) could be used. The herbicide glyphosate was indicated for use in these trials rather than a selective herbicide as initially, no other species was present within the treatment area due to the complete cover of *F. japonica*. Glyphosate has approval for application to areas in or near water.

Spraying was carried out using a standard Cooper Pegler knapsack sprayer fitted with a standard lance and a very low volume nozzle. Glyphosate was applied to allocated treatment plots at a rate of 5 L ha^{-1} (1,800 g active ingredient ha^{-1}), using a low water volume (80 L ha^{-1}) (Garnett, pers. comm.), in May 1994 in the initial trial and in July 1996 in the follow up trial, when plants had reached a height of 0.75 -1.00 m and sufficient leaf area was available to take up the herbicide. The whole of each allocated plot was sprayed and care was taken to ensure that all stems were treated.

Monitoring
In order to assess the continued effectiveness of treatment, a non-destructive sampling technique was adopted for monitoring plots and no cropping was undertaken. Three replicate 1 m^2 quadrats were sampled at measured distances, 3 m apart, central to each plot in order to avoid edge effects from adjoining treatments. Within each quadrat, monitoring was carried out at yearly intervals in May 1994 and 1995 during the initial trial, and in July and November 1996 during the follow up trial. In order to establish

Figure 5.3 Photograph of trial site during site preparation in October 1993 showing digging procedure on plots 2 and 3. Note extensive cover of *F. japonica* material.

treatment effects on numbers of plants and plant stature, the following variables were measured:

- stem density, i.e. number of shoots per m^2
- stem height
- stem diameter
- number of leaves per stem

For an assessment of shoot density, the total number of stems in each quadrat was counted and recorded, only those stems which lay completely inside the quadrat frame were included. Within each quadrat, nine plants were selected for measurement of stem height, diameter and leaf number. Plant height was measured from ground level to the base of the apical shoot and stem diameter was measured using callipers at approximately 10 mm above the second node from the ground. The number of leaves per plant were counted including only those leaves which were fully open.

Data analysis

Results were entered onto an EXCEL database for further analysis. Data were transformed to $\log_{10}$ to equalise variances according to Day and Quinn (1989). Analysis of results were carried out in StatView (Abacus Concepts Inc., 1992-95) using single factor Analysis of Variance (ANOVA) from the monitoring in 1994. Remaining data were analysed using two factor ANOVA. Multiple comparisons of means were made *a posteriori* using Fischer's protected least significant difference (plsd) test (Steel and Torrie, 1980). From these analyses an assessment of the efficacy of treatments was made and compared against the control.

Calculation of costs

An estimation of costs was prepared for the various treatment options relating to the control of *F. japonica* on sites awaiting redevelopment. Treatment costs were taken from Spon's Architect's and Builder's price book (Davis *et al.*, 1992). Prices are as quoted for "measured work - minor work" (i.e. prices apply to a small project costing in the region of £70,000 in the outer London area) and are as follows:

- Digging at £1.49 m^{-3} Treatment defined as: Excavation and filling. Excavation using a wheeled hydraulic excavator with a 0.24 m^{-3} bucket; excavating to reduce levels; not exceeding 1 m deep.
- [1]Spraying at £0.22 m^{-2} Treatment defined as: Clearing site vegetation.

[1]Estimated cost of spraying is high in comparison to agricultural use but reflects the specific difficulties involved when treating *F. japonica* e.g. site preparation (cutting/trashing dead stems), difficult access, pre- and post-treatment monitoring to assess levels of control.

- (i) Dig, cart away and landfill at £20.90 m^{-3}. Treatment defined as: Excavation to reduce levels up to 2 m depth at £3.98; Mechanical disposal of excavated materials to landfill not exceeding 13 km distance using lorries at £14.10 m^{-3}. Surcharge for extra distance at £2.82 m^{-3}.
- (ii) Dig, cart away and landfill, import soil and compact at £49.00 m^{-3}. Treatment defined as (i) plus: Mechanical filling with imported soil, deposition; compacting in layers at £28.10 m^{-3}.

5.3 RESULTS

5.3.1 Effects of digging

Plots subjected to the digging treatment (plots 2, 3, 5 and 6) showed a significantly higher plant density than undug plots (plots 1 and 4) ($P<0.01$) in May 1994 and May 1995 (Figure 5.4 a). Plants in these plots also achieved significantly less height than those in undug plots ($P<0.05$), had significantly smaller stem diameter ($P<0.01$) and significantly lower number of leaves ($P<0.05$) (Figures 5.4 b - d). However, for dug plots, a decreasing trend in stem density was observed over time with numbers of plants m^{-2} in 1996 not significantly different to that observed in undug plots. Whereas initially (May 1994), plant height recorded from dug plots was significantly lower than that in undug plots, a steady increase in plant height over time was observed in dug plots until, in November 1996, plant height in dug plots exceeded that of plants in undug plots. A similar trend was observed for leaf number. Stem diameter remained constant throughout the monitoring period for plants in dug plots but a variation was observed in undug plots so that, by the end of the trial, stem diameter of plants in dug plots was greater than that of plants in undug plots

Visual inspection also identified differences in the vegetation composition of the plots. In plots not subjected to digging, only *F. japonica* was recorded whereas in dug plots, species additional to *F. japonica* were present (Table 5.5). Differences were also observed in the distribution of growth of *F. japonica*. In undug plots, clumps of the plant were growing from established crowns whereas in dug plots, growth was more evenly distributed. Regrowth on dug plots was from below ground rhizomes, no signs of active growth was observed from either rhizome or crown material on the soil surface.

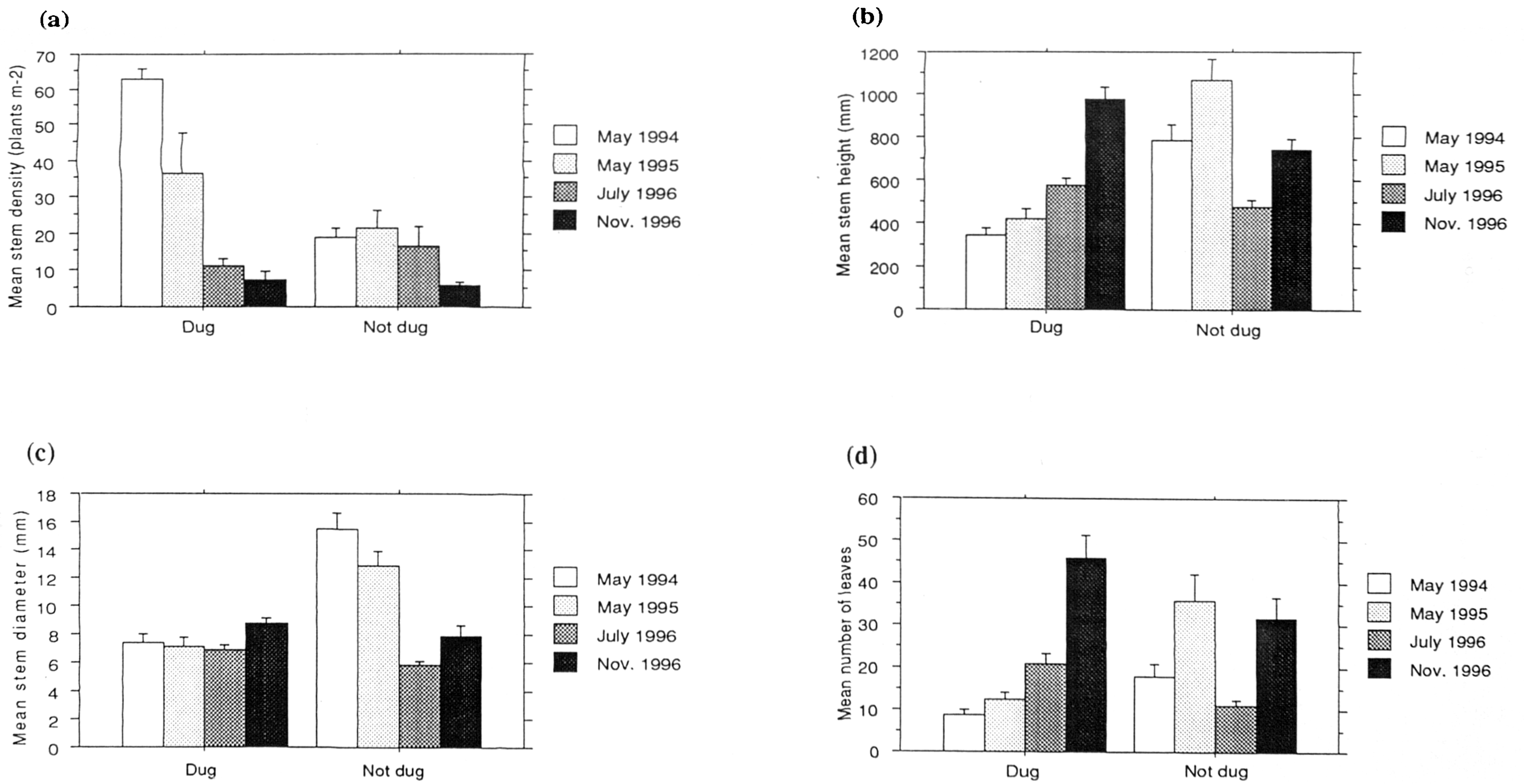


Figure 5.4 (a-d) Effects of digging on (a) stem density, (b) plant height, (c) stem diameter and (d) number of leaves over time. Data presented are mean values ± 1 SE and are pooled by treatment. (1994 n = 162; 1995 n = 81; July 1996, n = 81; November 1996, n = 54)

5.3.2 Effects of spraying

The effects of spraying are presented in Figures 5.5 a - d. Effects of spraying on undug plots were observed in May 1995, one year after glyphosate application. Mean stem density was reduced at this time (Figure 5.5 a) but was not significantly different to that recorded in the control plot. By July 1996 stem density of sprayed plants was significantly greater than that for unsprayed plants possibly due to a chemical 'breaking' of dormancy encouraging bud development. After a second application of glyphosate, stem density was once again lower for sprayed plants than for unsprayed plants but the difference was not significant.

Significant reduction in stem height was observed on sprayed plots as compared to unsprayed plots after only one application of glyphosate (Figure 5.5 b). However, by July 1996, no significant difference in plant height was observed between treatments. Many of the plants subjected to the spray treatment were showing signs of herbicide effect, with re-growth as bushy plants with narrow, pointed leaves and red coloration to stems (Figure 5.6). By November 1996, after a second application of glyphosate, stem height of sprayed plants had increased above that of unsprayed plants but the differences in stem height, stem diameter and leaf number were not significant.

Spraying had little effect on stem diameter (Figure 5.5 c). No significant differences were observed until November 1996 following the second glyphosate application when stem diameter of sprayed plants was slightly higher than that for unsprayed plants.

Leaf number was significantly reduced following a single application of glyphosate (Figure 5.5 d) when monitored one year after spraying. In July 1996 however, leaf number of sprayed and unsprayed plots were similar and following a second glyphosate application, leaf number of sprayed plots remained comparable with that of unsprayed plots. As no follow up monitoring was carried out the following season, the long term effect of this second spray was not recorded.

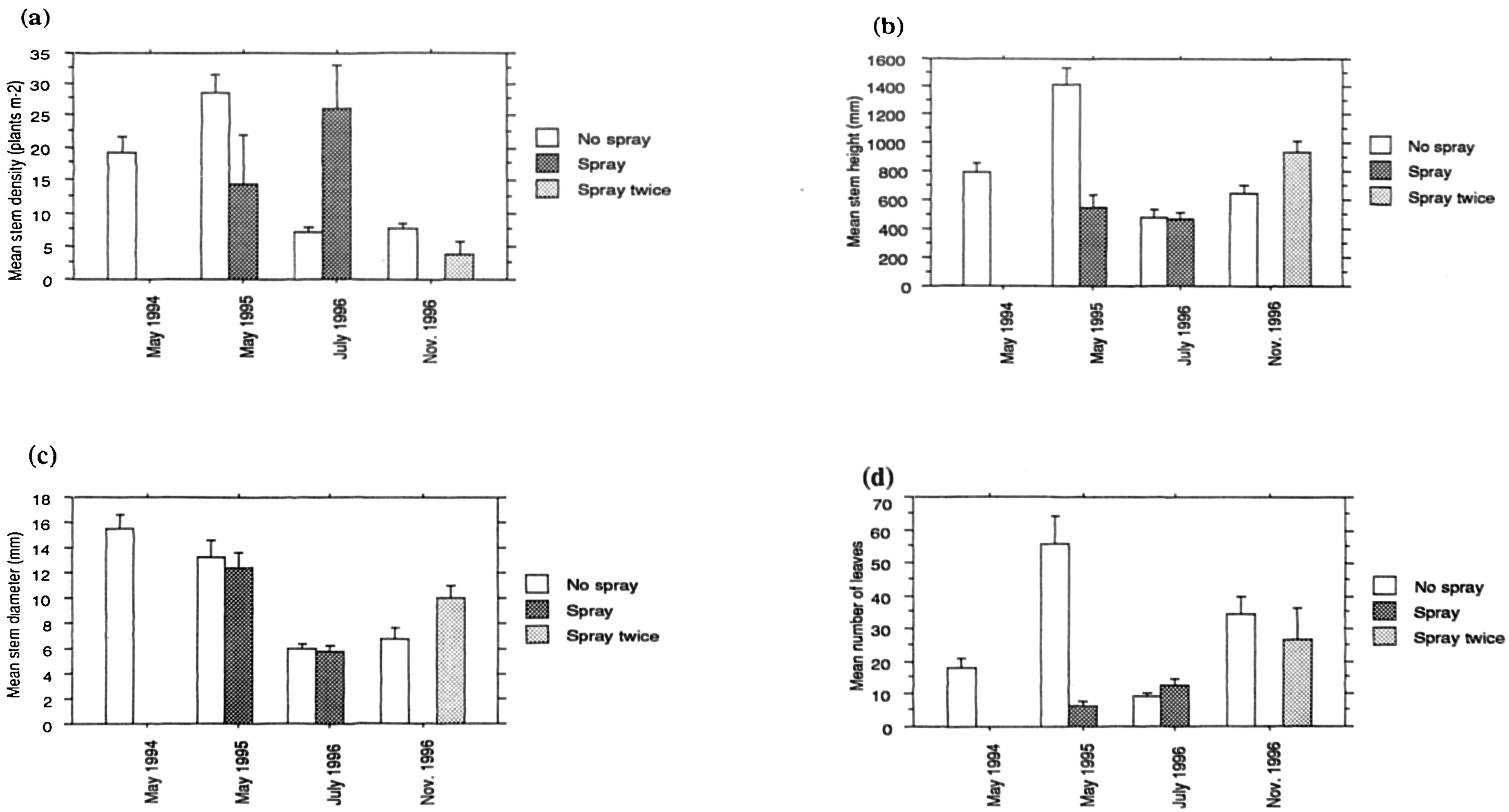


Figure 5.5 (a-d) Effects of spraying on (a) stem density, (b) plant height, (c) stem diameter and (d) number of leaves over time.
Data presented are mean values ± 1 SE and are pooled by treatment. (1994 n = 54; 1995 n = 27; July 1996, n = 27; November 1996, n = 27)

Figure 5.6 Re-growth of *F. japonica* one year after a single application of glyphosate

5.3.3 Effects of combined treatments

Visual inspection of the plots identified almost total control of the plant, at least for above ground parts, in plots subjected to both digging and spraying one year after a single spray.

By May 1995, in plots subjected to combined treatments, a good level of control had been achieved one year after a single application of glyphosate with only two and five *F. japonica* plants recorded in two of the six quadrats, the remainder being completely clear. A number of other species had established in these plots (Table 5.5) but undug plots still comprised a monoculture of *F. japonica.*

Table 5.5 List of species recorded in addition to *F. japonica* in plots subjected to digging treatment, no additional plants were recorded in undug plots. An asterisk (*) indicates presence of species in plots for each year of monitoring.

SPECIES LIST	MONITORING DATE 1994 MAY	1995 MAY	1996 NOVEMBER
PLOTS SUBJECTED TO DIGGING ONLY			
Anthriscus sylvestris	*	*	*
Cirsium sp.	*	*	*
Heracleum sphondyllium	*	*	*
Impatiens glandulifera		*	
Rumex sp.	*	*	*
Urtica dioica	*	*	*
PLOTS SUBJECTED TO DIGGING AND SPRAYING			
Alliaria petiolata			*
Anthriscus sylvestris	*	*	*
Ballota nigra			*
Buddleja davidii			*
Cirsium sp.	*	*	*
Galium aparine			*
Heracleum sphondyllium	*	*	*
Rubus fructicosus agg.			*
Rumex sp.	*	*	*
Silene vulgaris			*
Tussilago farfara			*
Urtica dioica	*	*	*

By the end of the trial, November 1996, significant differences were observed ($P<0.05$) between the mean stem densities of plots which had been dug and sprayed and those which had been dug only (Figure 5.7 a). A significantly lower stem density ($P<0.05$) was recorded in plots dug and sprayed, when compared against the control plot. Only two *F. japonica* plants in total remained on plots subjected to combined treatments (Figure 5.8).

Efficacy of treatments is shown in Figure 5.9. The effect of spraying resulted in a reduction in stem density but was low for both one and two applications of glyphosate on undug plots when compared to the control plot (25% and 79% reduction respectively). It is possible that a more effective control would have been achieved with two herbicide applications in the same year (e.g. May/June and August/September). The greatest percentage reduction in stem density (98%) was observed in plots subjected to digging followed by two glyphosate applications. Only this combined treatment resulted in the minimum 95% kill outlined in current guidelines (Welsh Development Agency, 1998). The time taken to achieve this, from initial digging to final monitoring was 3 years and 1 month. However, a good level of control (93%) was achieved after a combination of digging and one application of glyphosate. This was achieved within 19 months of the initial trial. As no particular benefit was gained from digging before winter, it is hypothesised that the same effect could have been achieved in a shorter period of time. Digging could be carried out in late winter (January or February) prior to shoot growth, with a spray in May when the plants developed sufficient leaf area to ensure uptake and a second application before senescence in the autumn (late August - September). This would potentially reduce the time required for effective (95% kill) treatment to one year.

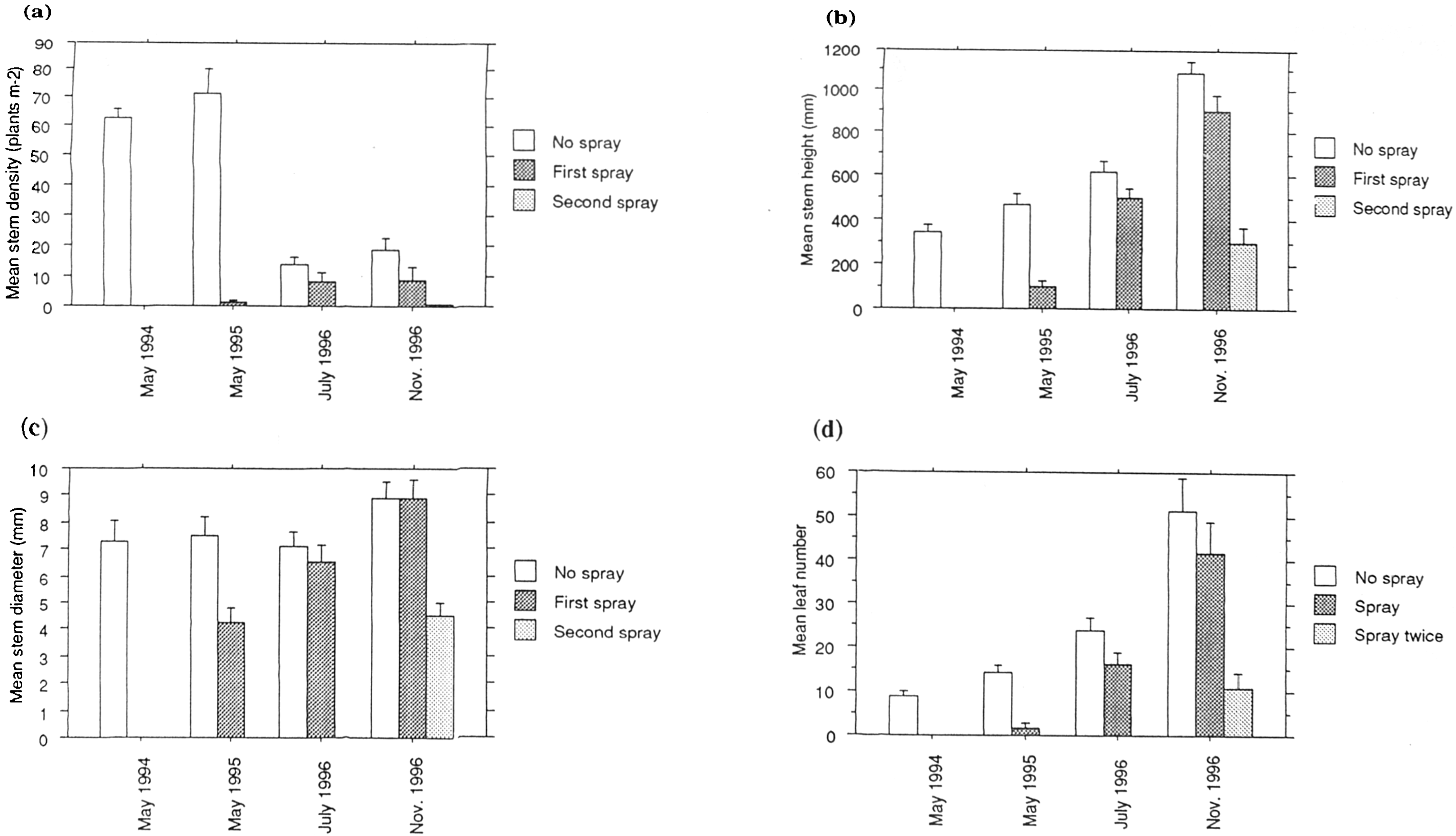


Figure 5.7 (a-d) Effect of combined treatments (digging and spraying) on (a) stem density, (b) stem height, (c) stem diameter and (d) leaf number. Data presented are mean values ± 1 SE and are pooled by treatment.

Figure 5.8 Photograph of trial site in November 1996 showing plots subjected to digging and spraying treatments.

TREATMENT	TREATMENT DATE	MONITORING DATE	TIME AFTER TREATMENT(S) (months)	EFFECT (% reduction in stem density compared to control plot)
Dug only	October 1993	May 1994	7	200% increase
Sprayed once	May 1994	May 1995	12	25%
Sprayed twice	May 1994 + July 1996	November 1996	30 (12+14+4)	79%
Dug + Sprayed once	October 1993 + May 1994	May 1995	19 (7+12)	93%
Dug + Sprayed twice	October 1993 + May 1994 + July 1996	November 1996	37 (7+12+14+4)	98%

Figure 5.9 Effects of increasing intensity of treatments over time shown as % reduction in stem density.

The implications of these findings are important in two respects. Firstly, the expansion in shoot initiation which arises following disturbance has implications for future management, particularly in terms of the plants invasion potential at new sites. Secondly the issue of removal of *F. japonica* from redevelopment sites in terms of both treatment methods and associated costs. The three options available for dealing with the plant on sites awaiting redevelopment are:

1. treating plants *in situ* with an approved herbicide,
2. excavating and either
   (i) spreading dug material in a designated area, treating re-growth with an approved herbicide or
   (ii) compacting dug material in a trench on site
3. excavation and removal to landfill

On development sites with little spare ground, options 1 and 3 are often used. The results of this study show that option 2 could in fact be more effective in terms of both the reduction of stem density and time taken to achieve an acceptable level of control. The financial implications of each of these options on potential redevelopment sites have been estimated and are shown in Table 5.6.

Table 5.6 Summary of comparative treatment costs for development sites adjusted for finance costs. Assumptions: Land values costed at £75 m^{-2}; interest rate of 10% $year^{-1}$ rolled up quarterly. Treatment costs from Spon's Architects' and Builders' price book (Davis *et al.* 1992).

TREATMENT	DURATION OF TREATMENT (months)	TOTAL TREATMENT COST (£ m^{-2})	TOTAL FINANCE COST (£ m^{-2})	TOTAL COST OF TREATMENT ADJUSTED FOR FINANCE COST (£ m^{-2})
DIG AND SPRAY (DIG + 2 SPRAYS)	18	1.93	11.98	13.91
CONVENTIONAL SPRAY (2 TREATMENTS ANNUALLY FOR AT LEAST 3 YEARS)	36	1.32	25.87	27.19
(i) EXCAVATE (to 2m depth), CART AWAY AND LANDFILL	3	20.90*	1.88	22.78*
(ii) As (i) + IMPORT SOIL AND COMPACT	3	49.00*	1.88	50.88*

* excluding Landfill Tax currently at £7 m^{-3}

5.4 DISCUSSION

This study has investigated the effect of integrating the use of a translocated herbicide and digging in an attempt to improve effective control and in particular to reduce the time needed to achieve an effective level of control *F. japonica* growth. Digging had a significant impact on the growth of *F. japonica*. Plants in plots subjected to digging showed a significant increase in stem density, but resulted in an initial decreased plant height, stem diameter and number of leaves. Where the rhizome system was intact, plants had greater height, greater stem diameter and a greater number of leaves per plant but significantly lower stem density. Fragmentation of the rhizome system, which provides resources to the plants early in the season has some effect on resulting plant stature indicating a relationship between rhizome fragment size and plant dimensions. The effect of digging however, decreased over time, with plant height and leaf number increasing beyond that of untreated plants over the trial period. Combination treatments have been tested for other invasive species. Duncan (1997) reported that a combination of ploughing followed by herbicide application was more effective than either treatment used alone in controlling *Tamarix ramosissima*, an alien invasive species in riparian areas in the United States.

The results of this study show that disturbance caused by digging, fragments the rhizome system and results in an increased stem density. This is consistent with the work of Adachi *et al.* (1996b) who described in detail the morphological development of *F. japonica* rhizomes. The dormancy of buds appears to be regulated by apical dominance. When the integrity of the rhizome system is broken, it would appear that dormant lateral buds will be stimulated to produce shoots whereas, with an intact rhizome system, an hierarchical system of bud development is seen with only apical rhizome buds and subterranean winter buds at the basal part of the shoot producing aerial shoots. This is confirmed in the present study, where fragmented rhizomes gave rise to a significantly greater number of shoots than those which were intact (Chapter 2; Chapter 4). A comparison of biomass for intact stands of *F. japonica* indicates that below ground biomass is greater than above ground biomass. Brock (1994) estimated below ground biomass in the UK at 14,000 kg ha^{-1} in the top 250 mm of soil whereas Horn (1997) estimated the above ground biomass of intact stands in the Czech Republic in May 1995 as 3,200 kg ha^{-1}. The below:above ground biomass ratio is biased towards conservative growth in intact stands, where the majority of buds along the rhizome remain dormant. With fragmentation, a greater percentage of buds develop into shoots, increasing the production of stems and leading to a potentially increased above ground biomass. A calculation of leaf production (stem density x leaf number) on plots subjected to digging compared to undug plots (Figure 5.10) shows that digging increases the production of leaves twofold.

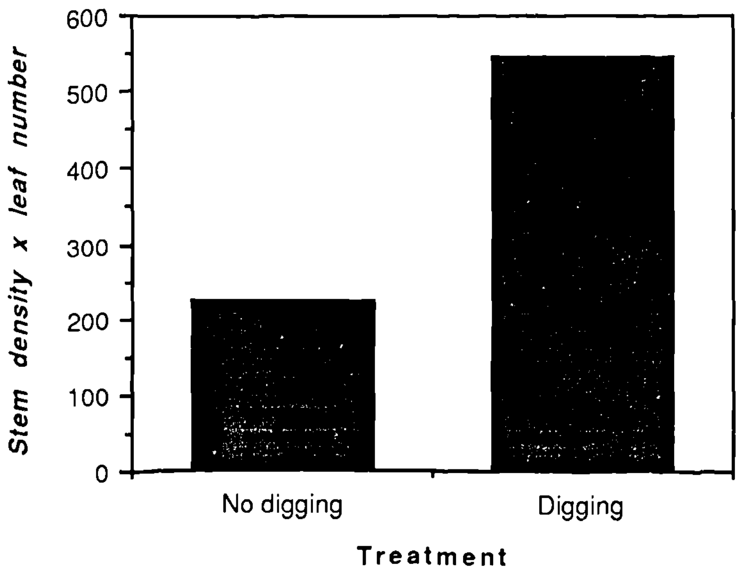


Figure 5.10 Effects of digging on leaf production. Data presented are pooled by treatment and are calculated using mean values for stem density and leaf number from 1994 monitoring quadrats (for no digging treatment n = 6; for digging treatment n = 12).

An increase in leaf production is especially important when the intention is to deliver a herbicide such as glyphosate to the target organ of the plant. When applied as a foliar spray, glyphosate is absorbed through the leaf cuticle and is translocated through the plant to the rhizome where it has its effect. The mode of action of glyphosate is dependent on its active ingredient, glyphosate acid. Glyphosate acid has a molecular structure closely related to the amino acid glycine which forms the basis for more complex amino acids and proteins in plants. The action of glyphosate inhibits the shikimic acid pathway, the means by which three essential amino acids, tryptophan, tyrosine and phenylalanine are synthesised. Glyphosate inhibits the production of these amino acids and other secondary compounds resulting in cell death (Zeneca, 1994). By stimulating the production of aerial growth through fragmentation, the herbicide is delivered to each fragment of rhizome which results in a more efficient level of control. The results of these trials suggest that rhizome fragmentation enhances shoot production and increases the above:below ground biomass ratio thereby ensuring a more effective delivery of herbicide to each rhizome fragment. One effect of glyphosate is the inhihibition of germination of buds on rhizomes which makes it valuable for the control of perennial plants (Murphy and Barrett, 1990). What is not yet known is the critical level of glyphosate concentration (per gram of rhizome biomass) required to kill *F. japonica* rhizome. Further research on the patterns of translocation within intact plants (e.g. Adachi, 1996c; Suzuki, 1994b) would be valuable in determining optimum timing for herbicide application.

Dug rhizomes left on the soil surface over winter were not observed to be producing shoots the following spring. No comparable data are available on the length of time that rhizome fragments remain viable. The winter of 1993-4 was mild although mean minimum temperatures in November 1993 and February 1994 were below average. Although some desiccation may have occurred in surface rhizomes, a significant number of rhizome fragments below ground regenerated successfully. New shoots appeared from below-ground rather than from the soil surface suggesting that once allowed to dry out, rhizome material on the soil surface was no longer viable. As no advantage in terms of control was observed in this trial by digging prior to winter, digging could be carried out early in the year (January/February) before shoot initiation, reducing the time required for treatment. Desiccation of rhizome material on the soil surface would not be a necessary precursor to effective treatment as any shoots appearing after digging would be targeted with the subsequent herbicide application.

Visual assessment of the plots in August 1994, following the first spraying treatment, suggested that the treatment had not been effective. However, on monitoring the following May, good control had been achieved in the plots subjected to digging and spraying and significantly reduced plant height and number of leaves were recorded on plants in sprayed only plots when compared to the control. These results confirm the observations of de Waal (1995), who reported green and flowering plants 73 days after treatment with glyphosate. When monitoring ten months later, she found that the plants showed a marked reduction in height and leaf size when compared to the control plot. In this large perennial species, the effect of glyphosate can take some time to appear as it requires translocation to the extensive rhizome system. The effects of treatment are often observed in the following growing season as short, new growth with multiple branching and small pointed leaves (see Figure 5.6). Effects of the second spray treatment may have been underestimated as monitoring was not carried out the following season.

The results of these trials confirm that a single application of herbicide alone is not sufficient to control *F. japonica*. The findings agree with those of de Waal (1995), Roblin (1988) and Beerling (1990a) where several applications of herbicide were required before effective control was achieved. Beerling (1990a) and Roblin (1988) suggest that two herbicide applications annually over a number of years may be necessary to completely eliminate the plant. The Welsh Development Agency guidelines (1998a) recommend that the plant is treated for a minimum of three years with follow up monitoring to ensure complete control. A second treatment on the plot subjected only to spraying resulted in a significant reduction in stem density compared to the control but was not as effective as the combined digging and spraying treatment.

An interesting result of the trial was the appearance of other species within plots subjected to digging. At the first monitoring visit in May 1994, although the dug plots showed a significantly greater *F. japonica* stem density, five other species had become established within the plots (Table 5.5). Undug plots still comprised monoculture *F. japonica*. By 1995, following the first spraying treatment, these species were still confined to dug plots but the disturbance had created a suitable site for establishment of *Impatiens glandulifera*. *I. glandulifera* was observed outside the treatment plots along the banks of the river throughout the trial. This annual species is an introduced plant, also a garden escapee, which is expanding its distribution in the UK, particularly in the riparian environment. As Beerling *et al.* (1993) reports that there is no persistent seedbank for this species, it is assumed that seed had arrived from plants on neighbouring ground during the trial period by means of the explosive seed capsules. Although it is a highly competitive invasive species, it was not recorded in subsequent years suggesting that other species had the competitive advantage. By November 1996, twelve other species had established in dug and sprayed plots compared to five species in dug only and dug and late spray plots. Following treatment of monoculture plant invasions, the area of bare ground following successful eradication can be extensive, increasing the risk of soil erosion. The establishment of replacement vegetation is therefore an important feature of a successful control programme. If disturbance due to digging increases the chances of establishment of native species as is suggested by these trials, the risk of erosion can be minimised and subsequent replanting costs can be reduced. (The latter have not been included in Table 5.6, for calculation of these costs see Chapter 6)

The implications of the results of these trials are that a combination of digging followed by a single spray treatment gives a good level of control of *F. japonica*. A second application of herbicide on dug plots achieved 98% control when compared to untreated plots. These results indicate that a shorter treatment period could be achieved by combination treatments.

Implementing these combined treatments could be cost effective both in terms of treatment costs but more importantly, in terms of 'waiting time' on redevelopment sites. Such land in many urban areas in the UK is infested with *F. japonica* and in many cases the land is adjacent to water courses which restricts the range of herbicides which can be used. The application of glyphosate would be relevant in these situations. Where there are no risks to adjacent water courses or other vegetation translocated herbicides such as triclopyr or imazapyr could be used. The results of these trials indicate that fragmentation of the rhizomes of *F. japonica* leads to increased shoot initiation which in turn allows a more effective transfer of herbicide to each rhizome fragment *via* above ground material. The increased effectiveness has important benefits for the management of *F. japonica* on redevelopment sites. Firstly, the combination of a mechanical digging pre-treatment followed by spraying has the potential to reduce the time required for treatment of the plant *in situ* hence reducing the costs incurred by the length of 'waiting time'. Secondly, if space is available on site for transfer of *F. japonica* infested soils to be treated whilst building works are taking place, these results indicate that thorough fragmentation of rhizomes would significantly enhance the effectiveness of subsequent application of a translocated herbicide such as glyphosate. Thirdly, germination of seeds of native species dormant in the soil due to either an increase in light availability once *F. japonica* stem and leaf litter have been cleared or due to physical breaking of seed dormancy in the seed bank by the action of digging, enhance the re-vegetation of treated sites.

As a winter exposure did not appear to encourage frost damage, a digging treatment carried out in early spring, followed by a spraying treatment on the re-growth, could result in a good level of control achievable in several months. With a second spray later in the year, a high level of control (>95%) may be possible in one year. In order to refine this technique, further research focusing on timing of treatments, critical depth of digging and the effects of intermittent/ continuous disturbance would be necessary.

5.5 CONCLUSIONS

- Disturbance in the form of digging, fragments rhizomes and results in promotion of bud development leading to an increase in stem density.
- Results suggest a relationship between rhizome fragment size and plant dimensions. Stems of plants in plots subjected to digging were initially significantly smaller in terms of stem height and stem diameter.
- A combination of digging followed by spraying significantly reduces plant density, plant height, stem diameter and number of leaves.
- The time required to achieve control is reduced when plants are subjected to a combination of digging and spraying treatments.
- The cost of treatment of *F. japonica* on sites awaiting redevelopment could be severely reduced with the employment of a combination of digging followed by a minimum of two herbicide applications.
- Digging established *F. japonica* stands clears accumulated stem and leaf litter.
- Digging also allows for the establishment of other species, reducing the problems of erosion caused by exposure of bare ground following herbicide application.

6.0 STRATEGIC MANAGEMENT OF *FALLOPIA JAPONICA*

6.1 INTRODUCTION

6.1.1 Background

Fallopia japonica impacts on both the natural and built environment and has an important human dimension. In terms of the natural environment, problems caused by the plant include the potentially detrimental effects of infestation on biodiversity (Cooke, 1988), the effective dispersal of the plant by natural processes in riparian habitats and the effect of the plant on riparian management such as disruption to flood defence operations by plant growth (Beerling, 1991b). In the built environment, the impact of *F. japonica* is seen through the damage caused to buildings, paving and landscaping and the costs incurred in treatment of the plant on sites awaiting development (Chapter 5). The human dimension includes the role which human activity plays in dispersal of the species, the impact of plants on human appreciation (aesthetics) and use of the environment and the resource and financial impacts of plant control. Each of these issues needs to be considered in the formulation of a strategic management policy.

In Chapter 3, it has been shown that distribution surveys of plants are useful in terms of gross assessment of extent of infestation but also that scale plays a major role in the accuracy and comprehensive nature of such surveys. A dot on a distribution map at a 10 km scale could represent a single or many records. This information can be refined by plotting at a 1 km scale but even at this scale, presence or absence of a species is typically all that is recorded. To be useful in terms of choice of control methods a much more comprehensive survey is needed which records not only presence or absence of a plant at a site but includes data on habitat, area covered and other site details such as proximity to water, access and land ownership. This type of survey is time consuming and is generally carried out on the ground although a number of initiatives have been implemented e.g. in the USA using remote sensing, either by aerial photography or satellite imagery (Everitt *et al.*, 1995).

Land managers are becoming increasingly responsible for sustainable management of the natural and built environment. In order to integrate the management of invasive species within this brief, the formulation of a strategic management policy is required. Formulation of policy requires an understanding of the ecology of the plant, consideration of the control techniques which are available whilst understanding the opportunities and constraints within the organisation responsible for management of the infestation. These are complex issues and therefore a management tool is needed which can be used to link these aspects and provide accurate information on the extent of a problem, its spatial distribution and relationship with other environmental factors and provide a context for the planning process. This chapter explores the use of Geographical Information Systems (GIS) as a management tool in the planning process in the context of a local authority planning a strategic approach to the invasion of *F. japonica* within a city.

6.1.2 The use of Geographical Information Systems (GIS) as a management tool

The idea of large scale computerised geographical mapping is not new. The Canadian Land Inventory CSIS (Canada Soils and Information System) was pioneered in 1965 and has been followed by a number of national land resource systems in the USA and UK (e.g. Briggs and Mounsey, 1989; Bradshaw and Muller, 1998). Developments in the sphere of information technology are occurring rapidly and GIS is becoming increasingly important as a management tool in land use planning, integrating environmental and other data whilst allowing monitoring and evaluation (Brown *et al.*, 1998). This is particularly true when dealing with extensive areas with complex land use and ownership issues, such as those faced by local authorities (Sui, 1998). Heywood (1990) for example, quoted studies in Canada which have used inventory data including the assessment of the depletion of ecological resources from forest fires; establishing moose and caribou habitat management programmes; formulating recreation planning; targeting watershed management; evaluating hazardous waste management; and assisting in waterway clean up programmes.

GIS is best described as an integrated collection of hardware, software, data and liveware operating in an institutional context. GIS is characterised by a great diversity of applications and is therefore difficult to capture within a single definition. Several of the many definitions applied are quoted by Maguire (1991) and include the following:

- A powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world. (Burrough in Maguire 1991)

- A special case of information systems where the database consists of observations on spatially distributed features, activities, or events, which are definable in space as points, lines, or areas. A GIS manipulates data about these points, lines, and areas to retrieve data for *ad hoc* queries and analyses (Dueker in Maguire 1991).

The definition by Burrough highlights one of the four approaches in GIS definitions, the toolbox approach, emphasising the generic aspects of GIS. Dueker's definition signifies the database approach in GIS, as an important and powerful tool. A third approach is process-oriented, stressing the information handling capabilities of GIS and a fourth is the application approach which looks at GIS as a problem addresser. The importance of GIS as a decision support and management information system is also widely recognised (Zhu *et al.*, 1998). Hence, it is not surprising that the use of GIS has become more common in local authorities since the mid 1980s and is still growing. One of the main reasons why the use of GIS has become popular on a worldwide basis and especially within central and local government is because GIS is a special case of information systems with three main foci: the map, the database and the ability to perform spatial analysis. The map focuses on the cartographic aspects of map processing and displaying, the database signifies the importance of a well-designed and implemented database and the spatial analysis focuses on the analysis and modelling properties of GIS.

The first official involvement of the UK government in handling geographical information and related issues dates back to the formation of the Ordnance Survey of Great Britain. This led initially to the development of a single national series of maps based on a countrywide National Grid and later to the production of digital maps (Chorley and Buxton, 1991). Since almost all of the work and responsibilities of local authorities involves some kind of spatial data (Table 6.1) an active interest has been taken in the application of GIS in recent years. Plymouth City Council implemented a GIS in 1989 (Markham *et al.,* 1990) and around the same time Berkshire County Council started their GIS pilot study, initially to assist in highway maintenance and strategic land use planning (Lodwick and Cushni,e 1990).

Table 6.1 UK local government responsibilities involving spatial information (Chorley and Buxton, 1991)

- *Monitoring changes* in resources (land and building, equipment and infrastructure) and conditions (economic, social, demographic, environmental, etc.)
- *Forecasting changes* in housing requirements, school roles, travel patterns, the economy and demand for land, leisure and community services.
- *Service planning* through identifying and forecasting changes in patterns of need for services and investments as a basis for the delivery of services and deployment of resources. This will determine both the scale of provision and its location, it will also highlight areas of social deprivation.
- *Resource management* of, for example, building maintenance, refuse collection, grass cutting, route scheduling of supply vehicles, mobile libraries, social service ambulances.
- *Transport network management* including provision and maintenance of highways, public transport, school transport, street cleaning.
- *Public protection and security systems* including police command and control systems, definition of police beats, location of fire hydrants, patterns of crime and incidents of fire.
- *Property development and investment* including the preparation of development plans, assessing land potential and preparing property registers, promoting industrial development and rural resource management.
- *Education* use of wide range of data for teaching purposes, including the use of demonstration software packages.

Prior to the use of GIS, the analysis of spatial and temporal data was a time consuming and laborious process. Advantages of using GIS, once the initial data have been digitised onto the system, include ease of regular updates and analysis using the overlay and buffering facilities (Goodchild, 1991). In this way, spatial and temporal variability of data can be taken into account.

The use of GIS in the urban environment is wide ranging and includes applications such as industrial location modelling, supply and demand forecasting in real estate markets, utility applications, land suitability and facility siting (Parrott and Stutz, 1991). Although these socio-economic applications in the urban setting may be more significant in historical terms, a multitude of environmental data and applications have become increasingly important and are being integrated into the GIS of local authorities (Worrall and Bond, 1997). These data sets can include environmental information on topics such as land use, habitat, designated areas, emissions into the air, and water and soil quality. Not least, the system provides an ideal decision support system for informing management policy.

6.1.3 Aims and objectives

Using information gained and conclusions presented in previous chapters, this chapter aims to identify those factors which should be considered in the successful management of *F. japonica*. Through a case study of the invasion of *F. japonica* in the city of Swansea, South Wales, a new approach to assessment of invasive plants will be presented involving the use of GIS. The case study will be used to show how this approach is aiding the formulation of strategic policy for the management of *F. japonica* in Swansea.

Specific objectives are to:

- identify the major factors required in formulating a strategic management policy
- undertake an assessment of the distribution of *F. japonica* in the city of Swansea
- establish the use of comprehensive data storage facilities (GIS)
- explore how the elements of a strategic management policy for *F. japonica* are being implemented in practice in the city of Swansea, South Wales, using GIS as a management tool

6.2 FORMULATING STRATEGIC MANAGEMENT POLICY

In order to formulate a strategic policy which will allow land managers to begin to move successfully from a stage of infestation towards eradication or at least, a satisfactory level of control, a number of factors need to be considered. There are three areas which require consideration, the ecology of the species, available control techniques and specific requirements for management and constraints and opportunities from an organisational point of view. There is a strong inter-relationship between these three areas (Figure 6.1), each of which is explained in detail below.

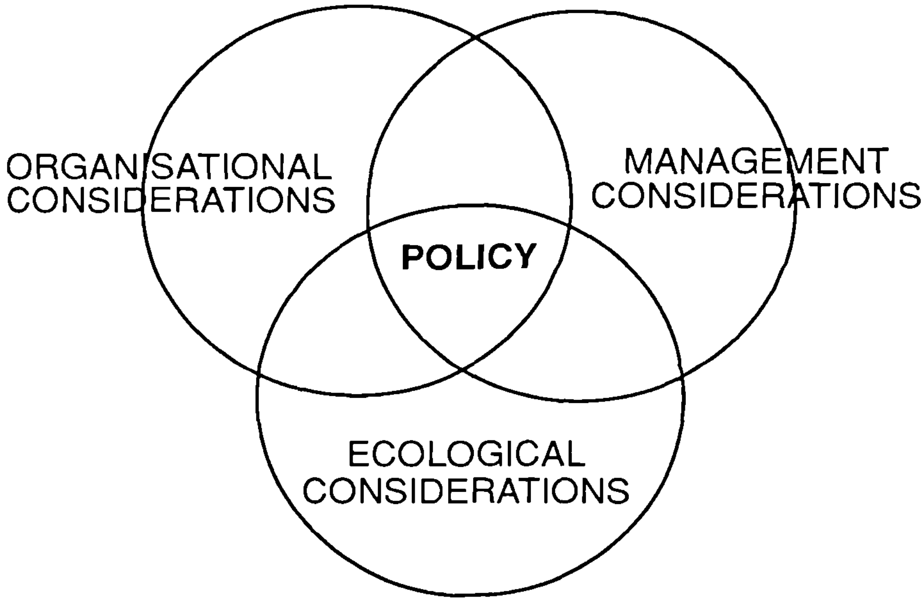


Figure 6.1 The inter-relationship of factors to be considered in formulating a policy towards strategic management of a plant invasion

Ecological considerations

Managing any plant invasion successfully must be underpinned by an understanding of the ecology of the plant. Knowledge of the structure of the plant, dispersal mechanisms, genetics, phenology, ecological tolerance, habitat preference are necessary in order to establish rates of spread, establishment and consolidation of newly arrived propagules at potential invasion sites and to target control measures at existing sites. For *F. japonica* the characteristics of the plant important in its control are its:

- vegetative reproduction (see Chapter 2)
- high vegetative regeneration rates from small rhizome fragments and cut stems (see Chapter 2)
- dispersal by both natural means (water transport) and by human activity (see Chapter 5)
- rapid growth rate (see Chapter 1)
- high underground to above ground biomass ratio (see Chapter 5)
- tolerance to a wide range of soil conditions (see Chapter 1)
- competitive ability in a wide range of habitats (see Chapter 1)

Management and control considerations

Management and control considerations include assessment of the problem, identifying appropriate methods of control, planning a control strategy, co-ordinating control between and within organisations and preventing further spread. Further assessment and monitoring of the problem are required throughout in order to assess the success or otherwise of the strategy.

Organisational considerations

Superimposed on ecological and management considerations are organisational considerations. Within organisations, specific opportunities and constraints exist for formulating policy and all are underlined by the need for raising of awareness. At each stage of the policy making, budgeting constraints may limit the scope of the management programme.

Specific factors are described in detail below.

6.2.1 Organisational considerations

Awareness raising

The first stage in any management strategy must be a recognition of the problem otherwise there is little incentive for management. Clearly there must be a raising of awareness that such problems exist and require action and this must be implemented at a number of levels; firstly, within organisations; secondly, between organisations and thirdly between organisations and the public. Under the broad heading of awareness raising are number of issues which filter through the whole process of formulating strategic management policy, these are education, training and budgets.

Education and training

Correct identification of the plant species requires information for those not already familiar with the plant. Guidelines such as those produced in the British Isles by the Environment Agency (1996; 1998), Welsh Development Agency (1998a; 1998b); Arboricultural Advisory and Information Service (Hawke *et al.*, 1995) and in Germany (Alberternst, 1995) are invaluable in highlighting the main features of the plant and associated problems.

Training in best practice in methods of control and application of control techniques is necessary to ensure that contractors and others employed in control programmes understand the nature of the plant and use control methods effectively. Herbicide application for example requires that operators hold a National Proficiency Tests Council Certificate of Competence in pesticide handling, storing and application. Education is also necessary to ensure that organisations and the general public understand the methods of dispersal of the plant and ensure that further spread is halted or at least minimised.

Once it has been established that the plant occurs in significant numbers within the area overseen by a particular organisation, an assessment of the extent of the problem is necessary. However, the financial implications of addressing a problem invasive plant can be extensive. Thus, in order to achieve the necessary budgets, raising awareness within organisations to release funds to begin a management programme requires valid and accurate information regarding the extent of the problem, comparing the implications of a 'do nothing' approach and the potential costs of commencing a programme of control.

Budgeting

Consideration of costs involved in the control of an invasive plant have to be agreed often by a number of departments within an organisation. The costs involved include:

- administration
- surveys and assessment including assessment and monitoring prior to and post control
- data storage and retrieval
- preparing contracts and tenders for control
- contractors costs

- training and education
- production of information/publicity material for in-house and public use
- site rehabilitation following treatment.

6.2.2 Management and control considerations

The factors which provide the basis for management and control considerations include methods of assessment and monitoring, methods of control, preventing further spread and co-ordinating control. Each of these factors is explained in detail below.

Assessment and monitoring

An accurate assessment of the extent of the problem is required in order to begin the process of management. Once completed, it allows establishment of baseline data at a point in time against which future monitoring can be compared.

Following survey data collection, storage of the data is a major issue. Paper maps are useful in terms of identifying clusters of plants but give little indication of total area covered except by visual assessment. Transferring data to a computerised database enables some manipulation of data by, for example, sorting by grid reference to allow assessment of heavily infested areas or allowing total area of infestation to be calculated. The use of computerised spatial databases such as Geographical Information Systems (GIS) allows data to be correlated with other spatial data and allows manipulation of the data to establish a wide range of correlations between, for example, landuse types, land ownership, access and planning controls (Maguire, 1991; Hendriks, 1998). Once the method of assessment and data storage have been agreed, appropriate methods of control need to be identified.

Methods of control

A number of methods of control are available for the treatment of plant invasions. Some of these however have been unsuccessful in the treatment of *F. japonica*. Burning, for example, removes above ground growth of the plant but is only a temporary measure as re-growth quickly regenerates from underground rhizomes. Shading is also unsuccessful as stems have the ability to grow in the absence of light, above ground growth being supported by the extensive reserves of nutrient stored in rhizome material. Cutting (Seiger and Merchant, 1997), mowing and grazing (Child *et al.*, 1992) are successful in continued removal of top growth but plants will resume growth when the treatment is discontinued. These examples show that an understanding of the biology of the plant are important in identifying appropriate methods of control.

Application of a translocated herbicide is the only method which acts directly on the rhizome system. As described in Chapter 5, even this method requires application over a long time period (3 - 5 years) before successful control is achieved. It is necessary therefore to continue the search for improved methods of control. The results described in Chapter 5 show that a fruitful path to follow is the use of combination treatments so as to increase the effectiveness of herbicide application. Improvements in delivery of herbicides either as new formulations or new methods of application are welcome additions to the extensive range of treatments which can be used against problem plants. New methods of delivery for the application of glyphosate are currently being trialed by The National Trust, English Nature and Environment Agency in the South West of England. The technique uses a drench gun to inject a solution of glyphosate into hollow stems between lower nodes of the plant whilst *in situ* (Renals, pers. comm.). The advantages of this method are that it can be applied to individual plants within existing vegetation of nature conservation value, it does not involve disturbance to the plant thereby producing no waste plant material and can be applied in any weather conditions. The disadvantage is that it is time consuming. The use of specialist equipment such as a long-lance sprayer (Barrett, 1990; Barrett and Newman, 1991) for application of herbicide to large plants in inaccessible areas has also been trialed. De Waal (1995) observed that use of the telescopic lance to deliver glyphosate to tall plants *in situ* was reasonably successful in achieving control.

An important feature of a successful control method is that it is suited to the particular situation. *F. japonica* grows in a wide range of environments therefore the method of control must be chosen carefully in order to comply with particular site conditions. For example, the range of herbicides which can be used in riparian situations are limited by legislation (Chapter 5). Access to sites with steep embankments for example, railways, rivers can restrict the type of control, mowing would not be applicable in these situations. The presence of other species of nature conservation value may also restrict the type of control measure which is applicable. For each site, a decision making process is required which directs the land manager towards the most suitable method of control. A typical process is shown in Figure 6.2.

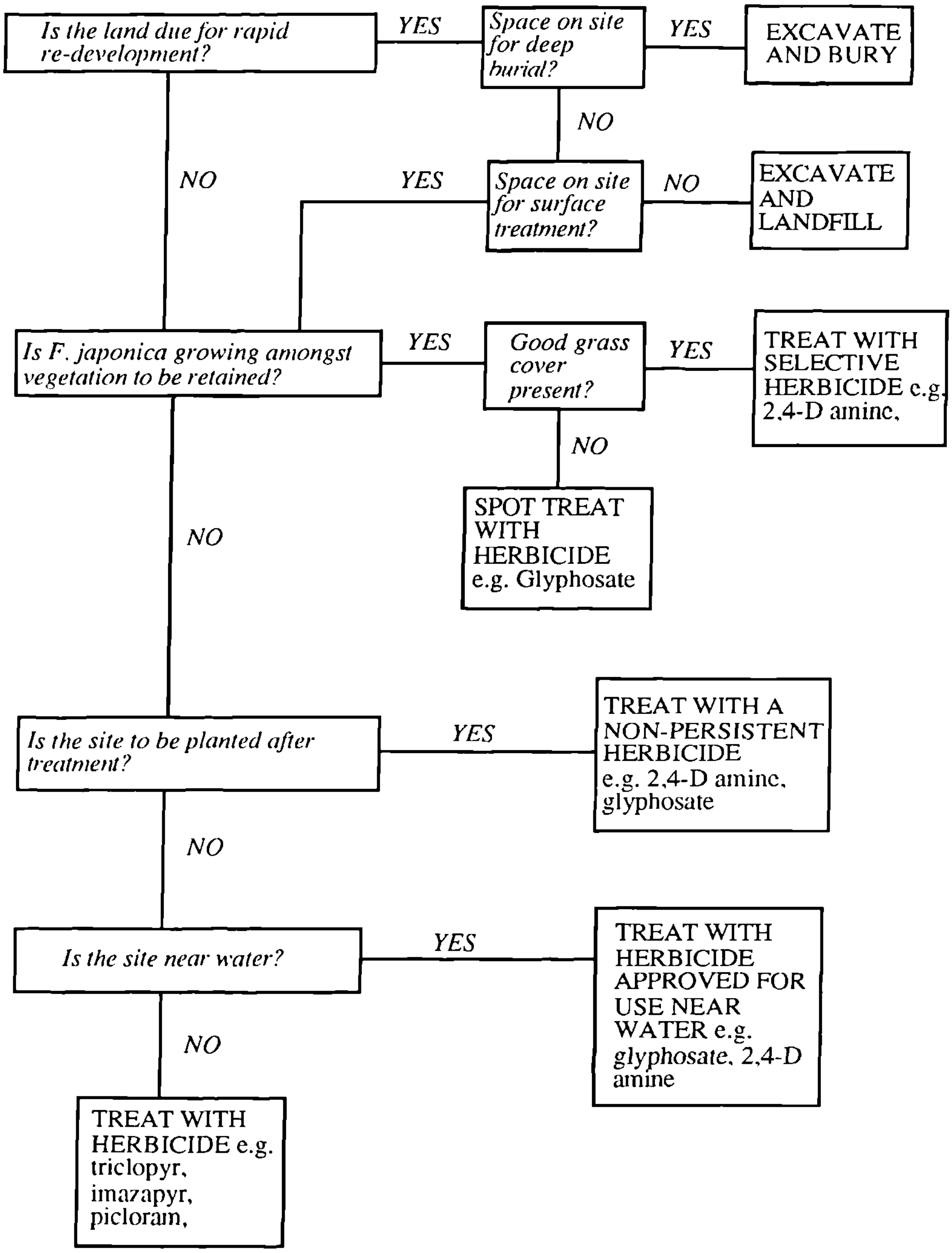


Figure 6.2 Flow diagram showing a decision making process for selecting suitable herbicide control methods for *F. japonica* on a re-development site.

The potential for improving methods of control must be an important factor in formulating a strategic management policy and continued education and research is necessary to inform this important component.

State-of-the-art treatment methods and co-ordinated management strategies help towards a better and more efficient control of *F. japonica*. However, cost implications, access problems and the extent of the invasion in some parts of Europe, demand a more permanent method of control such as biological control.

There is potential for the future control of *F. japonica* to be achieved by biological agents such as insects or pathogens from the native range of the plant (Fowler and Schroeder, 1990; Fowler *et al.*, 1991; Holden *et al.*, 1992; Fowler & Holden, 1994; Shaw, 1997). Such clonal plants have, in the past, made good candidates for biological control (Fowler, pers. comm.). The dispersal abilities of a biological control agent are usually adequate to reach most locations in which the target plant grows and control can be achieved in areas which would otherwise have remained untreatable due to access problems, particularly in difficult terrain. Biological control is environmentally safe, providing the proper procedures are followed, with no harmful residues and no risk to humans or animals. By reducing the competitive advantage of the target plant, native vegetation can become re-established resulting in positive effects on the local flora. Further, classical biological control has the advantage that once the agents are successfully established, the control is permanent and little or no further expenditure on other forms of control is required. It is usually self perpetuating and requires no repeated applications in contrast to mechanical and herbicidal management strategies. The method relies on control of the plant by reduced vigour and spread rather than on eradication.

Preventing further spread

A knowledge of the ecology of the plant must underpin all aspects of its management, not least in the prevention of further spread. *F. japonica* has been shown to regenerate successfully from small fragments of rhizome and from cut stems in both a soil and aquatic medium (Chapter 2). Human activity has played a major role in the dispersal of the plant to date, both in its introduction to the British Isles and in its subsequent escape into the wild (Conolly, 1977). Movement of soils contaminated with *F. japonica* material has been one of the most efficient transport mechanisms of the plant to new sites. Awareness raising and continuing survey and assessment are necessary to prevent or at least reduce this mode of dispersal in future. Proper disposal facilities for the plant in urban areas could reduce the rate of fly-tipping of garden waste (awareness raising, budgeting). In terms of dispersal by natural disturbance, control strategies which target upstream infestations in riparian areas could reduce the spread of the plant to downstream sites within a catchment (co-ordinating control). Correct identification of the plant (awareness raising) is of prime importance to ensure that new infestations are identified at an early stage and treated as soon as possible.

Co-ordinating control

F. japonica is a plant which does not respect artificial boundaries. It is necessary therefore to liaise with adjacent landowners when treating an area infested with the plant. The structure of the rhizome system means that the extension of rhizomes could encroach onto neighbouring land even if no plant shoots are visible. If neighbouring land is not included in the treatment programme there is a high risk of re-invasion. On a strategic level therefore, it is necessary to co-ordinate any control programme with adjacent landowners. Some examples of a co-ordinated approach are listed below. Integral links with other components of a strategic management policy are shown in brackets.

- alerting private land owners to the nature of the problem (awareness raising)
- negotiating a joint programme of control with adjacent landowners (budgeting)
- co-ordinating between departments or sections within an organisation to allocate funds for treatment of an area which impacts within the remit of more than one department (budgeting)
- negotiating treatment or survey costs to be shared between two or more organisations within a geographic area (budgeting)
- promoting educational seminars which bring together contractors, land managers and ecologists to train in best practice (awareness raising).

6.2.3 Formulating policy

The final stage in the preparation of a strategic management plan is to bring all the strands of the process together to formulate policy (Figure 6.1). Policy will vary considerably from one organisation to another depending on factors such as land-ownership and responsibility. In the Environment Agency for example, a number of administrative sections would be required to approve and have an input to a management policy within existing organisational policy constraints. These sections would include flood defence, recreation, conservation, water quality, water resources, waste regulations and pollution control sections for example. In a local authority, housing, leisure services, amenity and recreation, building control, planning, waste management and conservation sections would need to be involved. General policy should incorporate issues such as prioritising treatment areas, working on a catchment scale in riparian areas, protecting areas of nature conservation value, preventing spread into non-invaded areas and determining budgets for treatment.

6.2.4 Summary

In addressing the above considerations and factors, an holistic approach has been adopted towards the management of a plant invasion, taking into account the plant's ecology, appropriate control and management options and organisational constraints (Figure 6.1). The inter-relationship of factors such as budgeting and awareness permeate through the process and are necessary at all stages of strategic policy making. Similarly, control methods can only be effective if the ecological and biological features of the plant are understood and taken into consideration. In beginning to implement strategic policy, accurate assessment of the problem plays a major role. Without baseline information on plant distribution, the effectiveness of any policy will be difficult to determine. There is potential therefore to investigate the use of new computerised data storage and retrieval facilities such as GIS which enable some of the links described above to be made more easily. The following case study establishes the use of GIS in the assessment and subsequent policy formulation for the management of *F. japonica* in the city of Swansea, South Wales.

6.3 CASE STUDY: INFESTATION OF *F. JAPONICA* IN SWANSEA, SOUTH WALES

6.3.1 Introduction

The case study presented in this Chapter deals with the strategic management of *F. japonica* in the city of Swansea, South West Wales. A comprehensive survey of the city was undertaken to map the distribution of *F. japonica*, the results of which were entered onto GIS for subsequent storage and use. The results of the survey are presented here to demonstrate the use of GIS as a management tool to assist the formulation of strategic policy for the management of *F. japonica* in the city, taking into consideration the factors described earlier in this Chapter (Section 6.2). The case study represents a good example of best practice by a local authority, in terms of allocation of available resources, integration between council departments and co-operation between the various bodies dealing with a forward planning attitude towards sustainable management within the city.

In 1991-92, Swansea City Council (which, following local governement re-organisation in 1996 became the City and County of Swansea) implemented a GIS to be used primarily for development control and forward planning (Weston, 1995). The Council prepared a strategic list of information valuable in the planning process which was entered onto the GIS (Table 6.2).

Swansea City Council implemented their GIS primarily for development control and forward planning, however four departments, Estates, Leisure Services, Engineers and Planning, have access to the GIS and each is adding data including all departments dealing with issues relating to local plan policies (Table 6.2). The Estates Department has a long-term project to transfer the land terrier (a register of land area and ownership) which has been extended to include an asset register of all Council-owned properties in Swansea. Data from the 1991 Population Census have also been entered onto the GIS and the Planning Department is now entering habitat and nature conservation data, which includes the *F. japonica* survey data from this case study. A similar study, carried out in Germany in an non-urban environment, monitored submerged macrophytes (Schmieder, 1995). The use of GIS enabled the creation of geographically referenced maps of distribution areas of single species or species groups and analysis of changes in area and locations of species during the investigation period. It was envisaged that similar results could be achieved by the application of GIS in the distribution survey of the invasive plant, *F. japonica*, in an urban environment. Obviously, one of the most important features of the use GIS in this kind of application is that many different data sets can be accessed simultaneously and manipulated (Parrott and Stutz, 1991).

Table 6.2 Strategic planning information entered onto the City and County of Swansea GIS. (Source: Weston, 1995)

*	All Local Plan policies	
*	Constraints:	Tree Preservation Orders (ongoing)
		listed buildings
		Ancient Monuments
		National Nature Reserves
		Local Nature Reserves
		Sites of Special Scientific Interest
		Ancient Woodlands
		conservation areas
*	Hazards:	landfill sites, landfill buffers
		notified hazards
*	Policy areas:	planning brief
		Article 4 Directions (special planning control power which enables the Council to protect certain areas)
*	Environment:	Japanese knotweed data
		habitat data (ongoing)

6.3.2 The survey area

The city of Swansea, with a population of approximately 190,000, has a history of industrial development mainly associated with the coal mining and steel industry dating from the turn of the 20th century. In recent years, industrial decline has led to the closure of mines and other heavy industry leaving behind a legacy of many hectares of disturbed and often derelict land. For many years the spread of the invasive plant *F. japonica* within the Council boundary was known to be considerable, much of it associated with disturbed and derelict land but no accurate assessment had been made. In order to assess the extent of the problem therefore, a comprehensive distribution survey of the plant was carried out in 1992, with the aim of entering the survey data onto the recently acquired GIS. The survey data, once captured would:

- provide a baseline for monitoring future control programmes and further spread of the plant
- aid the Council in co-ordinating control efforts
- allow integration of the survey data with other data sets held on the system.

6.3.3 Survey methodology

Assessment

A distribution survey of *F. japonica* in the city of Swansea was carried out during the early spring and late autumn of 1992. The plant is easily recognisable at these times due to the distinctive height and orange/brown colour of the dead woody stems and the presence of very little other vegetation. An area of the city totalling approximately 96 km^2 was systematically surveyed with the assistance of a team of student volunteers equipped with 1:2,500 scale Ordnance Survey (OS) maps and specially designed recording sheets (Figure 6.3). Prior to the survey the volunteers had been trained in recognition of the plant and use of the recording techniques. The distribution of the species was recorded both directly onto the maps and onto the recording sheets. Each occurrence of the plant was drawn onto the OS maps, either as a cross for small areas (< 20 x 20 m^2) or drawn onto the map as the actual extent of the stand for larger areas. Mapped information was cross-referenced with recording sheets using a unique site reference number. Mountain bikes allowed increased coverage of all roads, pathways and tracks in the city with each pair of volunteers able to cover an area of between 1 and 3 km^2 in a day depending on the number of occurrences of the plant. The recording sheets were used not only for the purpose of achieving consistency in the field, but also to accomplish easy coding for data entry onto the GIS. Each recording sheet contains a variety of information including a site reference number for each entry, the site grid reference, the exact area covered by the plant (in m^2), the associated land use and the proximity of each site to water. Furthermore, detailed information on the height and management of the *F. japonica* stand was noted. Elements of the recording sheet are explained below:

Site reference:

A number which is unique to each individual stand (group of plants) of *F. japonica* and is used during GIS data entry for tagging (linking) information from the recording sheet (attribute data)with that recorded on the map (spatial data).

Number (and area) of stands (Cut) (Uncut):

To assess the extent and area of *F. japonica* which was currently being managed by cutting.

Average height of stand:

To acquire further understanding of growth rates.

Maximum stem diameter:

To assess whether large, old established stands produced greater diameter stems than small, young stands.

Vegetation composition:

To aid subsequent choice of control methods, e.g. the use of selective or non-selective herbicides and to assess the extent to which associated species were able to co-exist once *F. japonica* had become established.

Proximity to water courses:

To assist in the choice of control method, taking into consideration restrictions on the use of herbicides in or near water.

Slope:

To assess the ease of access to a site in terms of subsequent control methods.

Land use:

To assess the landuse types affected by invasion of *F. japonica*.

Japanese Knotweed Survey Recording Sheet

International Centre of Landscape Ecology, Department of Geography, Loughborough University, Loughborough, LE11 3TU. Tel: 01509 223030 Fax: 01509 223931

Recorded by	Date
Site name	
Grid ref.	Site ref.

Number of stands (**Cut**)		
Total area of cut stands	m	m
Number of stands (**Uncut**)		
Total area of uncut stands	m	m

N.B. Mark location on the map, as + when stand is <20x20m or linear feature is <25m long, otherwise map as total area.

Average height of stand		<1m		1-2.5m		>2.5m		
Max. stem diameter at 30cm above ground		<1cm		1-2cm		2-4cm		>4cm
Vegetation composition		Japanese knotweed only				mixture of Japanese knotweed and other vegetation		

Proximity to water courses		yes		no		
Slope		flat		moderate		steep

Land Use

☐ Housing	☐ Shops	☐ Business/Industrial	☐ Public buildings
☐ Garden	☐ Park	☐ Landscaped area	☐ Recreation grounds
☐ Farm land	☐ Woodland	☐ Graveyard	☐ Waste ground
☐ Car park	☐ Road verge	☐ Roundabout	☐ Railway embankment
☐ River bank	☐ Stream side	☐ Canal	☐ Dock
☐ Pond	☐ Sea front	☐ Other, specify	

Remarks: ....

Figure 6.3 Recording sheet for the *Fallopia japonica* distribution survey

Transfer of survey data onto GIS

The survey information was entered onto a computer system using Genamap, a GIS produced by Genasys II Ltd. Two levels of data were utilised, spatial data and attribute data. The spatial data, taken from the 1:2,500 OS field maps, outline the extent of the distribution of the plant within each entry. These data were entered by a specialist company onto new data layers by on-screen digitising, using digital OS base maps as reference layers. On-screen digitising requires an operator to move a cursor over the screen thus capturing the positions of points and areas, building up digital representations of point, line, and area features. The attribute data taken from the recording sheets were entered onto separate files within the associated database of Genamap. The attribute data files contain all the relevant data for each separate area of *F. japonica* surveyed. Each entry made on the recording sheet was coded appropriately and subsequently entered onto the database of the GIS within a specified field. Once both the area and attribute data were entered, the information was stored under a specifically created work-area 'Jap_knotweed' within the GIS Genamap. This work-area or directory contains all the *F. japonica* maps and attribute data. Future updates may be stored as separate files within this specified work-area.

Once the attribute data were entered and tagged to correspond to the digitised area data, it was possible to view the location of each stand of *F. japonica* on screen. This information could be correlated with other data stored on the GIS. The attribute data could also be manipulated as an independent database to give summary information for any field recorded on the survey recording sheets.

6.4 SURVEY RESULTS

The results of the survey are now held by the City and County of Swansea on GIS. Due to copyright restrictions on the digitised OS base maps and other Council data, personal interrogation of the database has been limited. The data presented here have been supplied by the City and County of Swansea Planning Department on request and are included to illustrate the wide range of uses to which the database is being put in aiding the development of strategic management policy. Data from the survey can be summarised and summary results are presented here. However, the real advantage of GIS comes when data are accessed through the many layers of stored information, making it possible to link this survey data with planning applications, nature conservation designations, redevelopment plans for the city and land ownership. The

GIS is most useful in this 'liveware' capacity as a decision support system. Printouts of summary data can therefore only give examples of the extent to which GIS can be used in the planning process.

Assessment of the survey database shows that the total coverage of *F. japonica* in Swansea city in 1992-3 was 48 ha which represents 0.5% of the total land area of the city (Figure 6.4). However, the distribution of the plant throughout the city was not even, with the number of occurrences of the plant in a single one kilometre square ranging from absent to over 70 locations. Figures 6.5 and 6.6 show examples of different levels of infestations of *F. japonica* in the city.

When the relationship between the presence of the species and land use was examined, the survey showed that *F. japonica* occurred most frequently on land which was subjected to little or no management. The major landuse type infested was waste ground (21.7 ha), followed by urban areas (14.1 ha) (including industrial/business land, housing, graveyards, public buildings, carparks and commercial areas) and water courses (4.8 ha) (stream and riverbanks) (Figure 6.7). This information is potentially useful not only in identifying the localities of the plant for future control efforts, but also in identifying the land owners and agencies involved in the future management of the species.

When the survey data were correlated with land ownership, it was discovered that approximately 60% of the *F. japonica* occurrences in the area surveyed were found to occur on Council owned land.

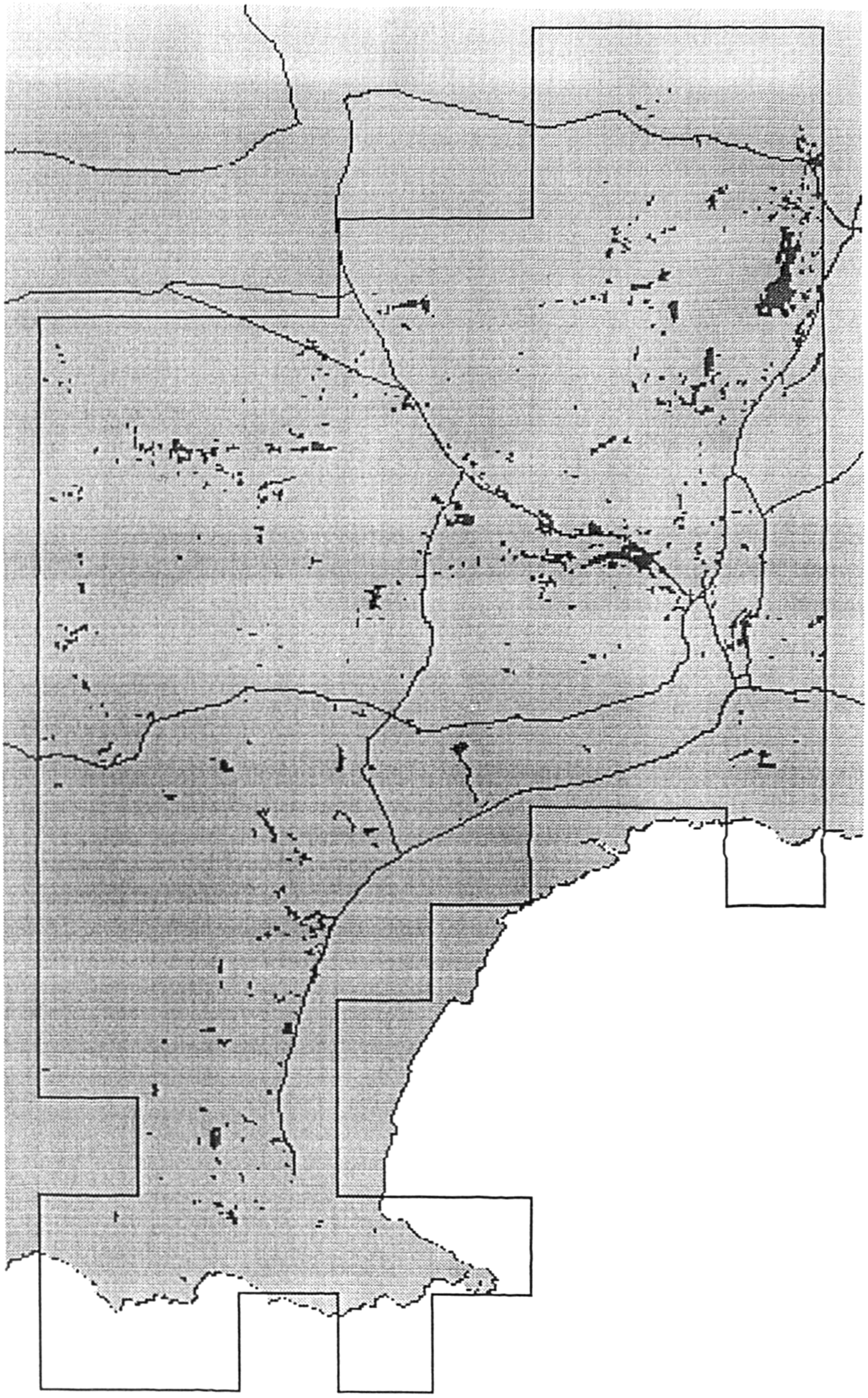


Figure 6.4 Map of survey area to show extent of 1992 survey and distribution of *F. japonica* in Swansea.

Light Infestation-Mumbles Scale 1 : 2500

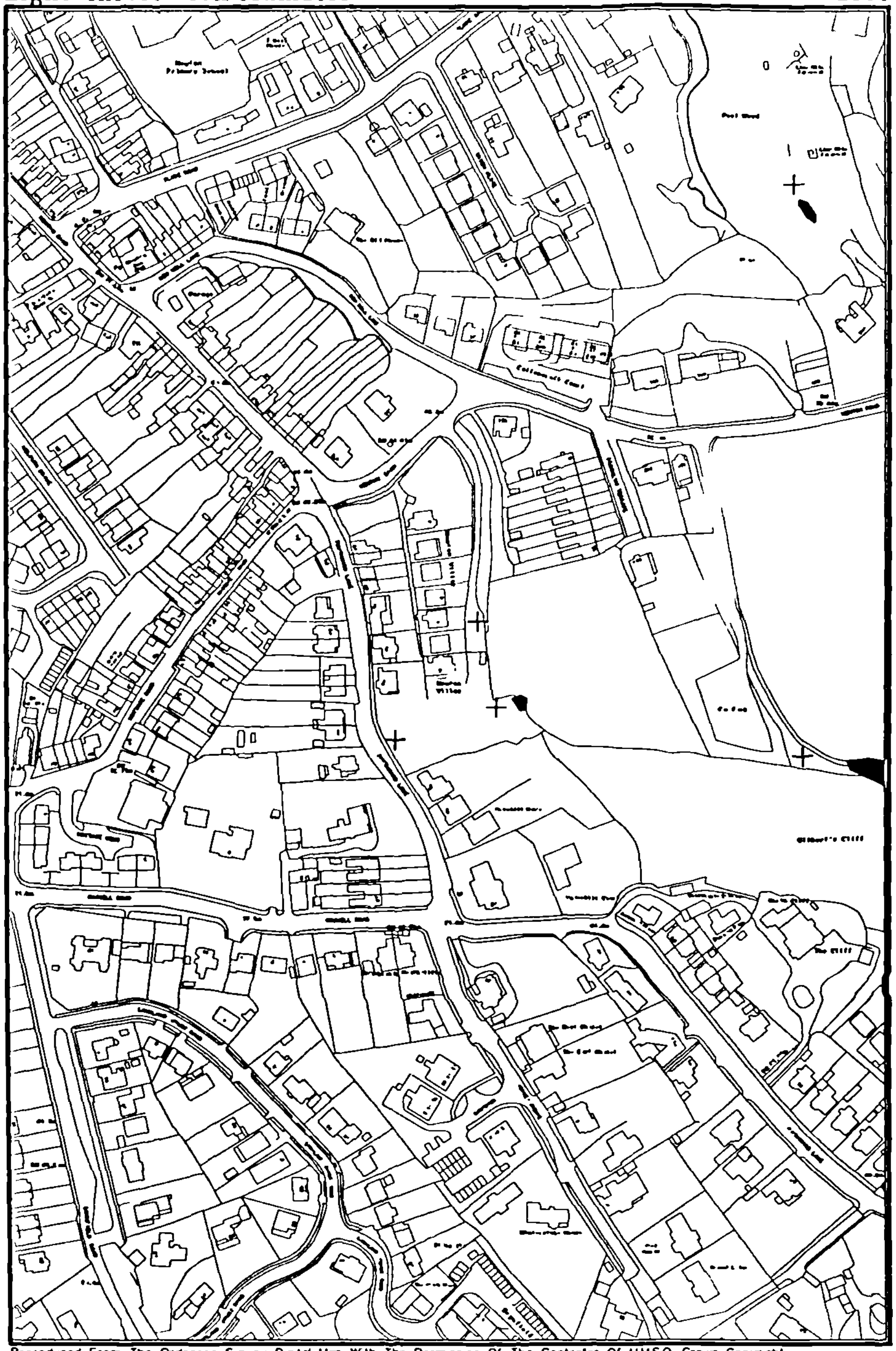


Figure 6.5 Example of an area of Swansea with a light infestation of *F. japonica.*

Heavy Infestion-Morriston Scale 1 : 2500

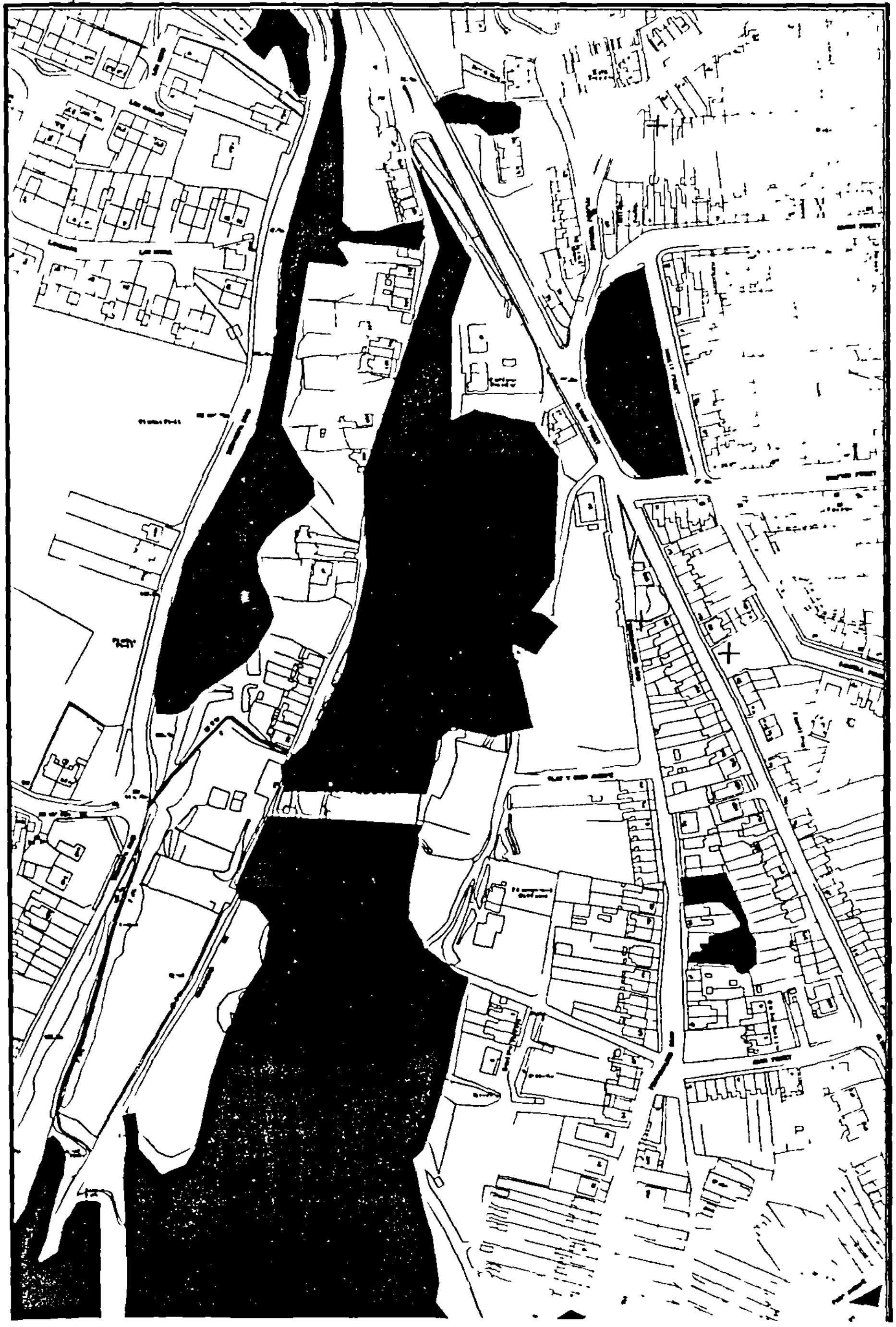


Figure 6.6 Example of an area of Swansea with a heavy infestation of *F. japonica.*

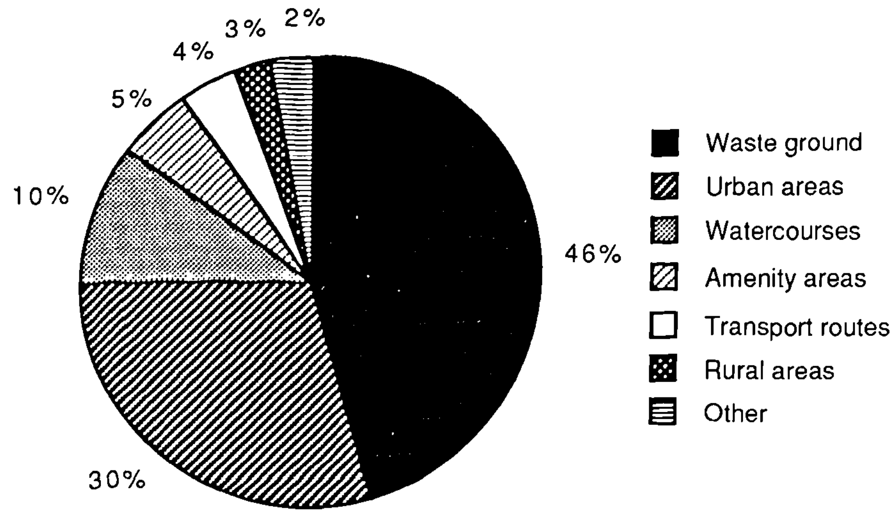


Figure 6.7 Occurrence of *F. japonica* in the city of Swansea from 1992 survey data. Data presented are grouped by primary landuse categories and are shown as percentages of total area of *F. japonica* recorded

One of the advantages of using GIS as a storage facility is the possibility of linking stored datasets. For example, by combining the 'survey data' layer with the 'nature conservation layers' on the GIS, it is possible to use the system to establish the degree of invasion of *F. japonica* into areas of high nature conservation interest. Figure 6.8 shows the results of correlation between the *F. japonica* survey data and sites designated as Local Nature Reserves (LNR). Of the five LNRs designated in the city area, all have recorded the presence of *F. japonica*. A range of habitat types are affected from coastal cliffs through heathland to broadleaved woodland. At Killay Marsh, no less than eight sites of *F. japonica* were recorded, seven of these being small areas measuring less than 20 m^2. In two cases, Mumbles Hill and Cwmllwyd Woods, the *F. japonica* infestation crosses the boundary of the site, emphasising the need for liaison with owners of neighbouring land. Of the five Sites of Special Scientific Interest (SSSI) designated in the area, only one currently has a small infestation measuring 35 m^2 in area. One of the two Wildlife Trust Reserves (WTR) (Peel Wood) has one small occurrence less than 20 m^2 in area. This information is valuable as it enables the Council to target control and prevention measures to areas which are vulnerable to habitat or species loss due to *F. japonica* invasion.

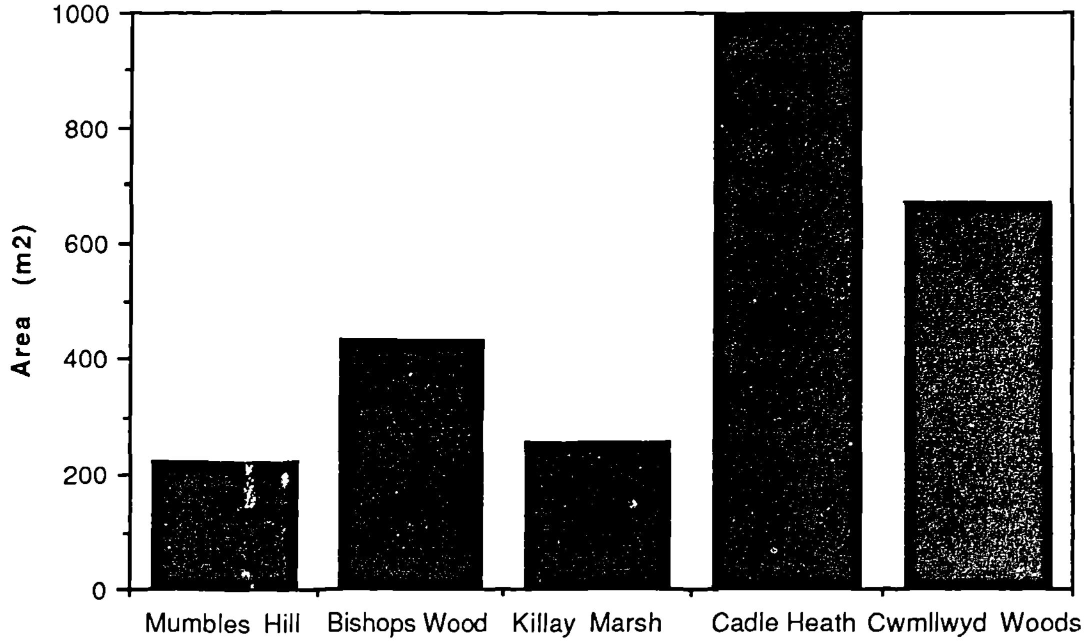


Figure 6.8 Area of *F. japonica* (m^2) within sites designated as Local Nature Reserves (LNR) in the city of Swansea. Data presented are 1992 survey data correlated with nature conservation designations using GIS

6.5 DISCUSSION

The results of the assessment of the distribution of *F. japonica* in the city of Swansea and data collation onto GIS are now available to the Council. The results have shown that within the city of Swansea, waste ground has significantly higher rates of infestation than any other habitat type. Urban areas which include housing, industrial sites, commercial areas and graveyards are also significantly affected. An interesting outcome of the survey is that 60% of the land which is affected by *F. japonica* in the city is in Council ownership. This amounts to an area of 28.8 ha and means that the future control of *F. japonica* in Swansea is certain to be of concern to the Council. The following sections in this discussion link to the factors identified in Section 6.2

and discuss how the use of GIS is enabling Swansea City Council to utilise the survey data information in the formulation of a strategic policy towards the control of *F. japonica* in the city area.

6.5.1 Using GIS as a decision support tool

Using the factors identified in Section 6.2, the following examples relate the survey information from the Swansea case study to the need for consideration of organisational, management and ecological factors which are necessary in formulating a strategic management policy. Examples are given which illustrate the importance of GIS in this decision making process.

Awareness raising, education and training

As part of its integrated strategy, the Council has identified the need to raise awareness of the problem and ways of dealing with it through provision of advice, information and training. This will be targeted at all sectors of the population, council employees, developers, contractors, landowners, the general public and land managers of sites containing the plant. Possible ways of achieving this include preparation of information sheets and procedural notes for the general public and Council staff, arranging training sessions for contractors and staff from relevant Council departments and preparing guidelines for developers to accompany planning applications. In addition, under the Government's New Deal, a group of six young people are being trained in herbicide application and other control methods, which will enable the Council both to respond to requests from landowners for treatment and to target priority areas.

Budgeting

Costs involved in carrying out the survey in 1992 amounted to £11,000. This included digitising data onto GIS. The allocated annual budget for *F. japonica* control measures in Swansea for all infested areas amounted to £25,000 in 1993. Taking the total coverage of the plant recorded in the 1992 survey (48 ha), the potential costs of an eradication programme for *F. japonica* in the city of Swansea are shown in Table 6.3. Conventional treatment would involve two applications of translocated herbicide over a three year period to achieve a 95% kill as described in current guidelines (Welsh Development Agency, 1998a). Follow up treatment of established stands, to achieve a higher rate of control (towards eradication), would involve a 2 year follow up programme of herbicide treatment on an estimated half of the original area. In addition, sites would require re-vegetation to prevent soil erosion and re-invasion following treatment, incurring additional costs. Therefore to eradicate *F. japonica* in the city of Swansea using conventional herbicide spray treatment would cost an estimated £720,000 for a minimum 5 year work programme at current rates. The 1992 survey identified that 60% of the total *F. japonica* cover was on Council owned land therefore in terms of potential costs to the Council itself an eradication programme would cost in the region of £432,000. This is not achievable on available budgets. Priorities must therefore be identified in order to target control measures where they will be most effective in achieving control rather than aiming for eradication.

Table 6.3 Estimation of costs of treatment and site rehabilitation for eradication of *F. japonica* in Swansea using data from the 1992 survey.

TREATMENT	RATE $£m^{-2}$	TOTAL COST £
Cost of treatment of existing infestations (48 ha)[1] (3 year treatment programme assuming 95% kill)	1.00	480,000
Follow up treatment of established stands (24 ha)[1] (2 year treatment assuming at least 95% kill	1.00	240,000
TOTAL		**720,000**
Potential cost to City and County of Swansea (From survey data, 60% of total infestation is on Council owned land)		432,000

[1]Estimated cost of spraying with herbicide is high in comparison to agricultural use but reflects the specific difficulties involved when treating *F. japonica* e.g. site preparation (cutting/trashing dead stems), difficult access, multiple sites and pre-and post-treatment monitoring to assess levels of control.

Methods of control

In view of the scale of the problem in Swansea, it is unrealistic in terms of both cost and practicality to treat all existing *F. japonica* in the city effectively using conventional methods of treatment. It is therefore necessary to formulate a management strategy which minimises expenditure on blanket treatments and instead uses resources available to target key sites and prevent further spread. Furthermore, control methods which do not rely on human intervention such as the use of biological control agents could provide a more effective method of control for the future.

Preventing further spread

New developments have in the past been responsible for increasing the distribution of the plant in the City, often by transportation of rhizome fragments in soil. Using GIS to correlate any planned land use change or future development with the *F japonica* survey data, allows the Council to put precautionary measures into place before any works begin (Child and de Waal, 1997). This is especially important in schemes such as highway improvements where large quantities of soil are moved with a high risk of spreading the plant. The GIS facilitates linking of different data layers, for example, combining the layers "Japanese knotweed data" and "Planning Brief" (Table 6.2) allows the Council to identify whether or not the site is infested with *F. japonica* prior to a proposed new development. Figure 6.9 shows output from the GIS for a section of the city with these links in place.

The proposed highway improvement scheme shown in Figure 6.10 intersects an area of *F. japonica*. The results gained from Chapter 5 show a clear relationship between fragmentation of rhizome material through digging and a subsequent increase in stem density. This indicates that without control measures in place, there is an increased risk of causing the plant to spread by movement of earth containing rhizome fragments at this point. With regard to such developments by outside contractors, the Council now incorporates detailed specifications on the control of *F. japonica* (Welsh Development Agency, 1998a; 1998b) into their contract documents. These measures also ensure that where possible, treatment costs will be incorporated into the costs of redevelopment. The Council is now taking precautionary measures to ensure that spread of the plant is not caused by importation of soil contaminated with rhizome fragments or by disturbance of already infested sites. To achieve this, soil material loads are inspected on delivery, or material is inspected *in situ* using a rhizome identification key designed specifically for *F. japonica* (Welsh Development Agency, 1998a). Soil which is found to be contaminated with *F. japonica* material is required to be either treated appropriately on site or disposed of at a licensed landfill site with the recommendation that it is buried according to current guidelines under the

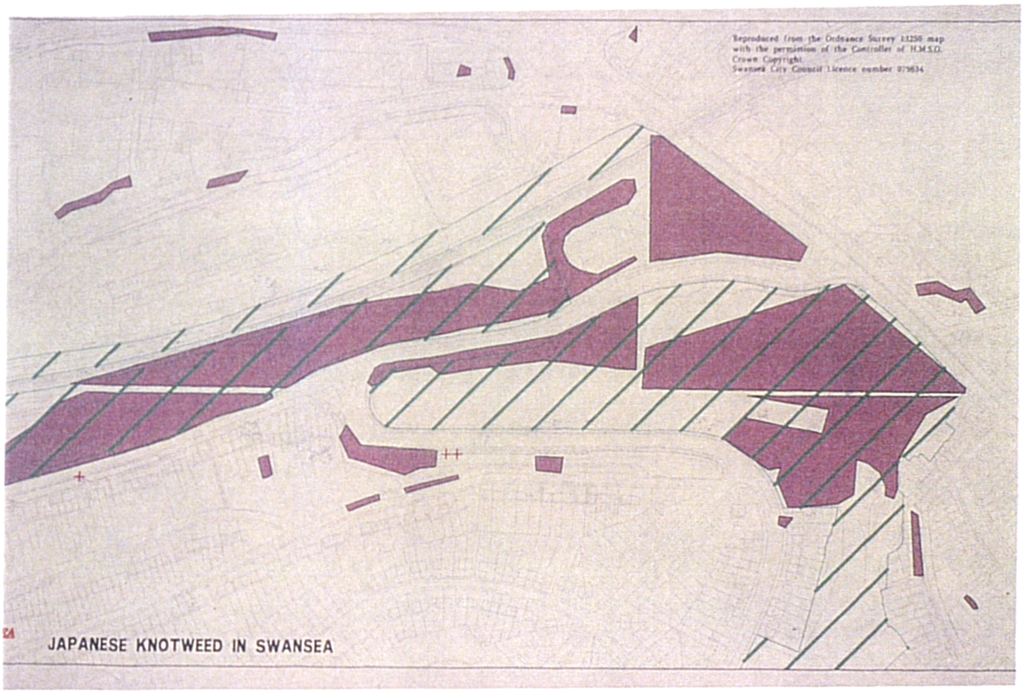


Figure 6.9 Output from the GIS showing the presence of *Fallopia japonica* in Swansea city Key: large areas of *F. japonica* marked as shaded purple; single stands marked as +; hatched areas represent proposed landscape improvement works.

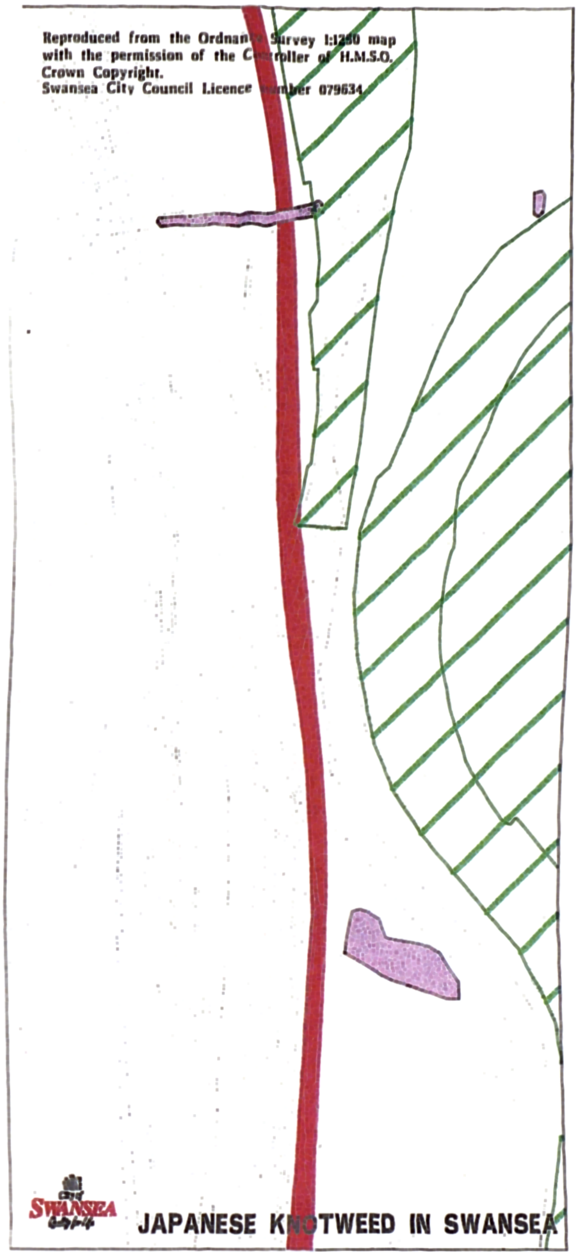


Figure 6.10 Output from the GIS showing correlation between the presence of *Fallopia japonica* (shaded purple) and proposed highway improvements (shaded red) in Swansea city Hatched areas represent proposed landscape improvement /protection area.

Environmental Protection (Duty of Care) Regulations (1991). These measures ensure that all areas subject to development are protected from further invasion.

Co-ordinating control

As plants are not restricted by artificial boundaries, an important aspect of control is the removal of the potential for infestation from adjacent sites and especially in the case of riparian environments from sites upstream. This may be realised through co-ordinating control efforts with adjacent landowners (Hill, 1994; de Waal *et al.*, 1995). Assessment of the distribution survey using the GIS has identified that the Council is a major landowner of infested areas. Further analysis of the data allows identification of other major landowners, such as Railtrack and the Environment Agency in addition to private landowners. In order to co-ordinate the management of *F. japonica*, all these landowners should be involved in future control efforts. To this end, the City and County of Swansea has appointed a Japanese knotweed Officer, who, as part of the Planning Department's Conservation Section, will co-ordinate with other agencies and organisations and will be the contact for enquiries from the general public. A working group with representatives from Welsh Development Agency, Environment Agency, voluntary organisations and representatives from the City and County Council departments will continue to liaise over the control of *F. japonica* in priority areas.

6.5.2 Formulating policy

Using the information gained from the *F. japonica* survey data and by using GIS to integrate the various factors required to formulate policy, the Council have devised five main policy aims. These are as follows:

- To raise awareness of the problems caused by *F. japonica* and provide information to enable all concerned to deal with it in a responsible and effective manner
- To identify priority areas for eradication and establish an action plan for *F. japonica* treatment on these sites
- To explore the potential for biological control
- To promote and encourage a co-ordinated response to the control of *F. japonica* in the Swansea area
- To prevent the spread of *F. japonica* into areas currently unaffected.

The Council has identified three priority areas with regard to the control efforts for *F. japonica* (Hill, 1994). These are:

- sites of high nature conservation value
- areas identified for environmental improvement and landscaping as part of the Council's "Greening the City" initiative
- sites where the infestation is causing damage or is creating a hazard

The GIS survey data are now being used to refine these priority areas allowing identification of sources of potential new infestations e.g. watercourses where rapid spread of the plant to new sites could be controlled. Further areas are being identified where funding opportunities could be used to include *F. japonica* treatment, e.g. sites funded under the Urban Programme and sites where resources are available for long term maintenance. Additionally, areas can now be highlighted where the plant on Council owned land is causing problems for others e.g. spreading into private gardens, and areas where prevention of infestation will be a priority e.g. areas which are currently "Japanese knotweed free" . Until recently the Council was unable to monitor the spread of the plant as there were no baseline distribution data for this invasive species. Since the completion of the distribution survey and the instigation of the GIS, the Council is now able to monitor the species and treatment methods can be targeted accordingly. Treatment is carried out either by the City and County Council's Direct Labour Organisation or by outside contractors. The GIS database provides an excellent tool with which to record the programme of treatment methods and to monitor effectiveness through future surveys.

6.5.3 Evaluation of the use of GIS

This case study demonstrates that GIS is a valuable and powerful management tool for more rational decision making and increased efficiency, providing an holistic approach to the management of an invasive plant. In Swansea, the accurate assessment of the distribution of *F. japonica* within the city has enabled priorities to be defined, has provided baseline data with which to compare future control efforts and has enabled an assessment of the finances required to control the invasion of the plant. By integrating the survey data with other Council policy information, a valuable link has been established between actions undertaken by the Council and the presence of *F. japonica*. This means that the presence of the plant has become an integral part of Council planning policy and its control is now considered at all levels of future planning within the City.

Disadvantages of using GIS for this type of management strategy are predominantly those of costs. Geographical Information Systems are expensive to buy and base maps either have to be bought or rented from the Ordnance Survey. The costs of employing surveyors is also significant, although these costs can be kept to a minimum if well trained volunteers are used. Digitising the data onto digitised base maps is a time consuming process but once the data are entered, the costs of running the system are small, especially if the system is required for a multipurpose use as in the Swansea example.

In order to continue to be useful, regular updating is necessary. The 1992 survey provided valuable baseline data for assessment of the *F. japonica* invasion in the city area. Following local government reorganisation in April 1996, Swansea City Council was reorganised and became the City and County of Swansea. The area of its jurisdiction was increased from 96 km^2 to approximately 400 km^2. In 1997-98, a second survey of *F. japonica* was carried out extending over the whole of the new City and County area including the city area surveyed in 1992. This extended area included Gower, an Area of Outstanding Natural Beauty and Mawr an upland area to the north of the City. The survey followed the same methodology, and data are currently being digitised onto GIS. The cost of the second survey was £12,000 with an additional £7-8,000 for digitisation of data which was carried out by a specialist company. Data from the second survey are still being processed and when available will further inform the future management policy of *F. japonica* in the City and County of Swansea. Full information is not yet available, however the re-survey will enable comparisons to be made on a site by site basis in terms of:

- total area of *F. japonica* within the newly designated City and County boundary
- rates of expansion over a six year period within the former City Council boundary
- rates of spread at individual sites
- invasion of new sites
- success of control measures
- habitats at risk of invasion especially in protected areas such as Gower

Figures 6.11a and 6.11b show GIS output for an area of the city adjacent to the sea front surveyed in both 1992 and 1998 with the status of *F. japonica* shown at this location in both surveys. These figures clearly show the expansion of *F. japonica* within the two sites at this location, both sites having more than doubled in size over the six year period between surveys. For the 1998 survey, initial estimates give 61 ha for the total area of *F. japonica* in the city area (Hathaway, pers. comm.) compared to a total of 48 ha in 1992. This represents a 27% increase in cover of the plant in the city area in just 6 years. The rate of expansion of the plant within the city can now be quantified, the 1992 survey providing an excellent base line for subsequent survey data to be compared against. Just these two examples show that the rate of expansion of *F. japonica* in Swansea is rapid both in terms of expansion of area covered within a site and expansion in total area covered by the plant throughout the city.

The advantages of GIS stored data are significant especially when the unique ability for spatial searching and overlaying are taken into account. The data in this case study have become available to a wide range of departments throughout the local authority, manipulation of the data and correlation between local planning policy and invasion alert areas is now available at the touch of a button and the problems of updating and storing paper survey sheets have been removed. GIS provides a robust system of data storage which is responsive to changes in planning policy, land use and land ownership well into the future.

The data are being used by the Council on a daily basis as an integral part of their management strategy to inform planning decisions and management contracts and will be useful in future to assess rates of spread, habitats at risk of invasion, success of control measures and identification of priority sites. The survey information and the integration of the data with Council policies stored on GIS will continue to inform future strategic policy in the management of *F. japonica* in Swansea. The information from the GIS is also available to inform the various departments on most suitable methods of control on a site by site basis. Neither the cost nor the practicality of treating all sites with conventional methods is sustainable therefore further investigation into the use of biological control would be timely.

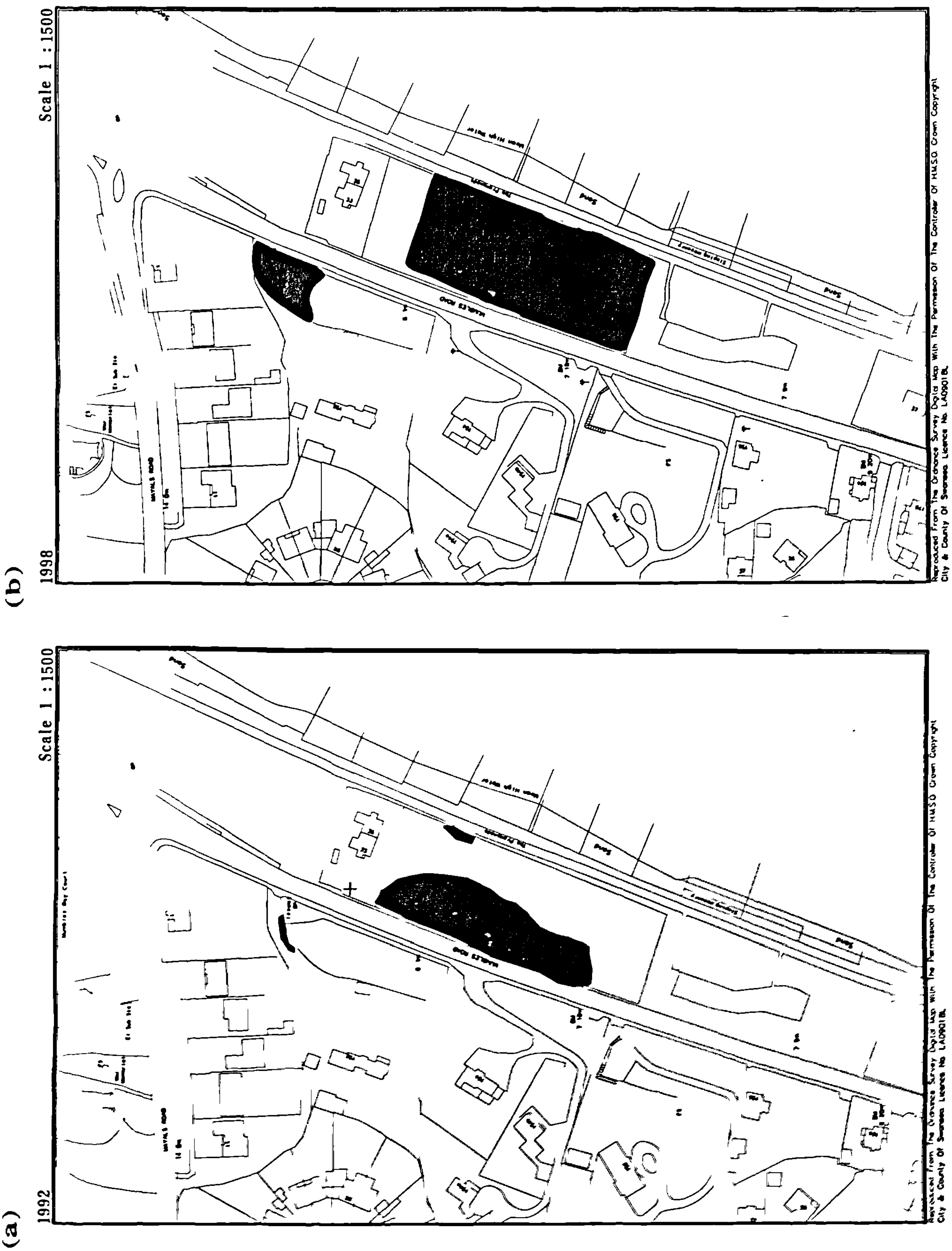


Figure 6.11 Output from GIS showing the expansion in area of *F. japonica* at two sites in Swansea between (a) 1992 and (b) 1998.

6.6 CONCLUSIONS

- A number of factors are important in the formulation of strategic management for invasive plants. These lie within three main headings of ecological, management and organisational considerations. It is only by integration of these factors that an holistic approach to plant management can be achieved.
- The use of GIS supports the planning of strategic policy by linking survey data with other operations affecting the environment such as planning constraints and redevelopment applications, designation of nature conservation sites and landscape improvement areas. By linking these datasets, specific policy can be implemented such as protecting non-infested areas, prioritising treatment on sites of nature conservation value and preventing further spread during re-development operations. The principles described in this chapter would also be applicable to other invasive organisms in a range of different situations.
- GIS is a powerful management tool in that it enables a wide range of departments within an organisation to have access to information on infested areas. However, the information needs to be kept up to date to ensure that decisions are made on the basis of accurate data.
- The use of GIS in Swansea has enabled specific policy to be defined in order to begin the strategic management of the plant in the city. Land ownership identified from the 1992 survey data has placed the responsibility for dealing with *F. japonica* in Swansea firmly on the shoulders of the Council.
- Control of the plant in the city will be unsustainable by conventional treatment methods due to the excessive costs involved. An investigation into the potential for biological control would therefore be timely.
- The results of the two surveys have shown that *F. japonica* is expanding rapidly in the city of Swansea. Prior to these surveys, no accurate assessment of *F. japonica* had been undertaken on such a large scale. The use of GIS has enabled an accurate assessment of spread of the plant at individual sites. The GIS will allow further assessments to be made as to the invasion behaviour of the plant, for example the extent to which expansion of the plant within individual sites may contribute to the increase

in total area of the plant within the city. This information will be invaluable in understanding the invasion ecology of the species.

7.0 DISCUSSION

7.1 INTRODUCTION

In the 150 years since its initial introduction to the British Isles, *Fallopia japonica* has successfully made the transition from novel horticultural species to ubiquitous, naturalised, aggressive invader. That its invasion has been so successful, is due to its unique combination of biological and ecological traits. The plant tolerates a wide range of environmental conditions and is a strong competitor with rapid growth and high vegetative regeneration rates. *F. japonica* is terrestrial and yet thrives in riparian environments; it is sexually sterile although hybrids are present in the British Isles; it is a plant associated with urban areas and yet it is widespread in semi-natural habitats; and although it is susceptible to herbicides it has gained a reputation for being impossible to control. Despite efforts to manage the plant, its distribution is still increasing, indicating that existing control measures and management practices are failing to halt the invasion process.

The aim of this study has been to provide an insight into the successful invasion of *F. japonica* in the British Isles in relation to its management and control. This chapter aims to clarify those features of the plant which have aided its success as an invasive species in its introduced range. In relation to invasion theory, the reproduction and dispersal of *F. japonica*, genetic variability and the means available for its control and management are examined and suggestions are put forward regarding future prospects for its long term management. The concepts developed in this study are relevant to the management of other invasive plant species.

This study has shown that:

- *F. japonica* has made a successful invasion into the British Isles and has the potential to continue to increase its distribution by vegetative spread.
- a range of factors have aided this successful invasion including the growth habit and form of the plant, its ecology and ability to persist in disturbed sites, its capacity to hybridise and most notably, its regenerative capacity.
- the growth habit and form of the plant and its regenerative capacity have caused significant problems for its control and management.

- using tools such as Geographical Information Systems (GIS) enables an holistic approach to be adopted in formulating strategic policy to aid the control and management of the species. In particular, the use of GIS enables accurate assessment of the extent of the plant in an area, provides a basis for efficient planning policy to prevent further spread, allows an assessment of costs involved in control efforts and provides a mechanism for monitoring the effectiveness of management policies.

The initial introduction of *F. japonica* to the British Isles as a horticultural plant occurred in the mid ninteenth century probably *via* Von Siebold's nursery garden in Leiden, The Netherlands. Although the exact date of introduction is not recorded, the collection of exotic plants from Japan overseen by Von Siebold is documented to have been occurring between 1823 and 1856 (Mac Lean, 1978). Beerling *et al.* (1994) gave the probable date of introduction as 1848. It is not clear whether several collections of *F. japonica* were made during this period but *F. japonica* and its related species *F. sachalinensis* and *F. japonica* var. *compacta* were all present in the British Isles by 1880 (Hooker, 1880a; 1880b; 1881). The hybrid *F.* x *bohemica* however, was not described in Europe until one hundred years later, in the early 1980s (Chrtek and Chrtková, 1983; Schmitz and Strank, 1985; 1986; Bailey and Conolly, 1985).

Intentional introductions, such as the deliberate introduction of plants for horticultural purposes, have an advantage over accidental introductions in that the initial stages of establishment are protected from the normal factors dictating invasion success such as competition and survival (Ashton and Mitchell, 1989). In propagating horticultural species the initial survival of the propagule, reproduction, initial dispersal and establishment are ensured, thus minimising the risk factors involved in the initial invasion phase and omitting the first time lag in the invasion process, that of initial establishment (Kowarik, 1995a). Once distributed as an ornamental garden plant, *F. japonica* had an established base from which to disperse into the wider environment.

Plant introductions often exhibit taller and more vigorous growth in their introduced habitat due to the absence of herbivores and pathogens normally associated with them. As with many introduced species, *F. japonica* has arrived in its new geographic regions without the associated insects and pathogens which use the plant as food and habitat (Emery, 1983; Fowler and Holden, 1994). These associated species cause sufficient damage in the plant's native range to keep it at sub-optimal growth conditions (Yano, pers. comm.). In the British Isles, *F. japonica* has a very impoverished fauna with only 11 species of insect having been recorded in association with the plant and none of these causing significant damage (Emery, 1983; Holden *et al.*, 1992). Ants feeding on extra-floral nectaries of the plant form a protective mechanism, discouraging other insects from utilising the plant (Richards, Moorehead and Laing Ltd., 1990). Leaf tissue is known to contain tannins and anthroquinones (Beerling, 1990a) which make the leaves unpalatable to some phytophagous insects and the rhizomes contain anti-helminth extracts (Anantaphruti *et al.*, 1982). Few pathogens have been identified from *F. japonica* in the British Isles (Holden *et al.*, 1992; Fowler and Holden, 1994) although ten species of saprophytic fungi (Emery, 1983; Ellis and Ellis, 1985) and 16 species of microfungi (Ellis and Ellis, 1985) have been recorded from dead stems. Without a range of herbivores and pathogens causing sub-optimal conditions for growth, the plant in its introduced range is allowed to grow unchecked.

In determining invasion success, Roy *et al.* (1991) suggested that the biological traits which enable a species to spread across their native continents are the same biological traits that enable some species to invade new continents. This could indeed be true for *F. japonica*. In its native range, the plant and its related varieties are primary colonising species of volcanic gravels (Tateno and Hirose, 1987; Sukopp and Sukopp, 1988; Adachi *et al.*, 1996a), and are tolerant of a wide range of environmental conditions in terms of substrate type, water and nutrient availability and pH (Beerling *et al.*, 1994). The common name of *F. japonica* in Japan, *itadori* (meaning strong plant) indicates that it is a robust species in its native range. There are, however, differences between *F. japonica* plants in the British Isles and Japan. As plant collectors often select the most impressive specimens, a single initial introduction to the British Isles of a particularly vigorous variety could account for these differences. In its native region, *F. japonica* reproduces sexually and is spread primarily by seed although vegetative reproduction is observed (Maruta, 1983; Suzuki, 1994a; 1994b). In the British Isles, Bailey (1990; 1994; 1997) has suggested it exists only as a male-sterile plant. Vegetative reproduction is therefore its only means of dispersal, leading to the suggestion (Bailey, 1994) that within the British Isles, the population of *F. japonica* is clonal. This has been confirmed by genetic analysis of all British *F. japonica* plants observed to date (Bailey pers. comm.).

Pysek (1997) however suggests that clonal plants often make poor invaders. Working from the premise that dispersal of a propagule to a new region is the starting point for a new invasion, specialised seed dispersal structures (Vogt Andersen, 1995) or vectors associated with seed dispersal represent an advantage for seeds over vegetative propagules. A seed is more resistant to frost, desiccation and mechanical damage than most vegetative propagules (fragments of stem or rhizome) and for this reason a vegetative propagule is less effective in dispersal. An analysis of alien plants which have successfully invaded into Central Europe shows that the percentage of alien plants dispersed by seed (64%) is greater than that for clonal plants (36%) (Pysek, 1997). However, Pysek (1997) also observed that clonal plants made up 60% of the deliberately introduced alien flora of Auckland, New Zealand compared to 40% of accidental introductions. It would appear that in terms of establishment, clonal plants have an advantage over non-clonal plants where deliberate introductions are made. Looking at the traits of an invasive species as defined by Baker (1965) or more accurately to those traits of an invasive plant which provide some prediction of invasion success (Crawley, 1987; Crawley, 1989; di Castri, 1990; Mack, 1992; Pysek *et al.* 1995) this study has shown that *F. japonica* fulfils many of the criteria. It is perennial, has rapid growth, is a good competitor and is capable of reproducing vegetatively. However, it appears that some plant traits have more to do with invasion success than others. Rejmanek (1995) suggested that the capability of a plant to exhibit vigorous vegetative reproduction was one such trait. In terms of the dispersal of vegetative propagules, two factors are important. The first is the action of water, acting as a transport mechanism, the second is transportation due to human activities.

The perception of a plant as a problem or 'weed' according to the terminology of Rejmánek (1995) varies with the degree of infestation in a particular area. In their native range, Japan, *F. japonica* and its related varieties form a normal component of the native vegetation and are of importance as primary colonising species of volcanic gravels (Sukopp and Sukopp, 1988). The plants contribute valuable nutrients e.g. nitrogen, to impoverished soils (Tateno and Hirose, 1987; Adachi *et al.*, 1996c) and are replaced by secondary species e.g. *Miscanthus oligostachyus, Aster ageratoides* and *Artemesia vulgaris* in the colonisation process (Tateno and Hirose, 1987). However, even in Japan *F. japonica* is recognised as a nuisance plant in private gardens and grasslands (Miyazaki, pers. comm.).

In the British Isles, *F. japonica* was first recognised as having an "encroaching propensity" in gardens before the turn of the century (Anon, 1879) and was described by John Storrie in 1886 as being naturalised and abundant on cinder tips near Maesteg, South Wales (an 'invader' according to the terminology of Rejmánek (1995)). It is now described as one of the most abundant plants in urban areas in Glamorgan (Wade *et al.*, 1994). In a survey of local authority districts in Wales, (Richards, Moorehead and Laing Ltd., 1990) the date at which *F. japonica* was first recognised as being a problem was given as between 1950 and 1985 although over half of the respondents still did not consider the plant a problem even though it had been present in their area since around 1900. Nationally, the plant was recognised as a severe enough problem by the late 1970s to ensure its inclusion in Part II of Schedule 9 of the Wildlife and Countryside Act (1981). In an effort to halt the spread of this invasive species, the Act states "if any person plants or otherwise causes to grow in the wild any plant which is included in Part II of Schedule 9, he shall be guilty of an offence" (HMSO, 1981). *F. japonica* and *Heracleum mantegazzianum* (another introduced and invasive species) are the only two terrestrial plants included in this Schedule of the Act. Despite this attempt at legislative control, *F. japonica* continues to expand its distribution throughout the British Isles, becoming widespread in a variety of habitat types including riparian, rural and urban areas. The plant now causes many problems including damage to structures, flood defence works, landscaping and hard surfaces in the built environment and a reduction in biodiversity of native species in semi natural, rural and urban areas.

One of the main problems in achieving successful control of *F. japonica* is the structure of the plant which has a high below ground to above ground biomass ratio. The extensive underground rhizome system is the target organ for treatment and requires repeated applications of a translocated herbicide to above ground material in order to achieve lasting control. Due to the extent of the rhizome a number of herbicide applications are normally necessary to kill the plant, a process which is costly in terms of both human resources and potential environmental impact. *F. japonica* is generally found in habitats which are subject to little or no management such as waste ground, road verges and railway embankments. These 'safe sites' enable the plant to grow unchecked and provide a nucleus of plants from which further spread can occur. A better understanding of the ecology of *F. japonica*, particularly in terms of its reproductive and dispersal strategies is therefore vital in order to target control measures more effectively. This study has addressed these issues and using the information obtained has developed strategic management policies in order to contain the further spread of the plant. Future methods of control are also explored.

7.2 REPRODUCTION AND DISPERSAL

This study has shown that high rates of regeneration are achieved from both rhizome fragments and cut stems of *F. japonica* and its congeners (Chapter 2, Chapter 4). There are three criteria by which regeneration success can be measured. These are:

- the probability that a vegetative propagule will produce shoots
- the time required for shoot emergence
- the subsequent growth and survival of shoots produced.

By testing these criteria against a range of environmental conditions, including planting stems in soil and water under varying light regimes, an assessment of the relative importance of modes of dispersal and an evaluation of the relative invasive potential of propagules has been made. In these studies, the time delay between planting and shoot emergence was measured in days. The probability of a propagule producing shoots was measured in days to achieve a 50% regeneration success rate. A high invasion potential is indicated by rapid shoot emergence and a rapid achievement of 50% regeneration success.

Rhizome regeneration

The results of this study (Chapter 2, Chapter 4) have shown a strong invasive potential from rhizome fragments of *F. japonica* and its related species. A comparison of results obtained for shoot regeneration from *F. sachalinensis*, *F. japonica* var. *compacta* and female *F.* x *bohemica* rhizome fragments showed that for all fragment lengths of these species, results obtained were comparable to those from 1 and 2 cm fragments of *F. japonica* rhizome. However, wild hybrid material (Chapter 4) gave results which indicate an even greater invasion potential for hybrid rhizome fragments than *F. japonica* (Figure 7.1). Within 6 days, shoot emergence was observed from all wild hybrid fragment lengths and by the same time, 50% of the fragments had produced shoots. These results were not replicated in the subsequent trial on *F.* x *bohemica* material from Buckingham Palace Gardens (Chapter 4) but were consistent for all fragment lengths from the wild hybrid source. This result suggests that there may be some hybrid forms which have a greater vegetative regeneration rate than *F.*

japonica. Further research on a wider group of hybrid plant material would be valuable to confirm these observations.

As a result of the trials on *F. japonica* rhizome fragments (Chapter 2), it was observed that the relationship between fragment length and time required for shoot emergence was not linear. This is illustrated in Figure 7.1. Shoots emerged from 4 cm rhizome fragments more rapidly than either 1 or 2 cm fragment lengths and achieved a 50% regeneration success in fewer days than all other lengths.

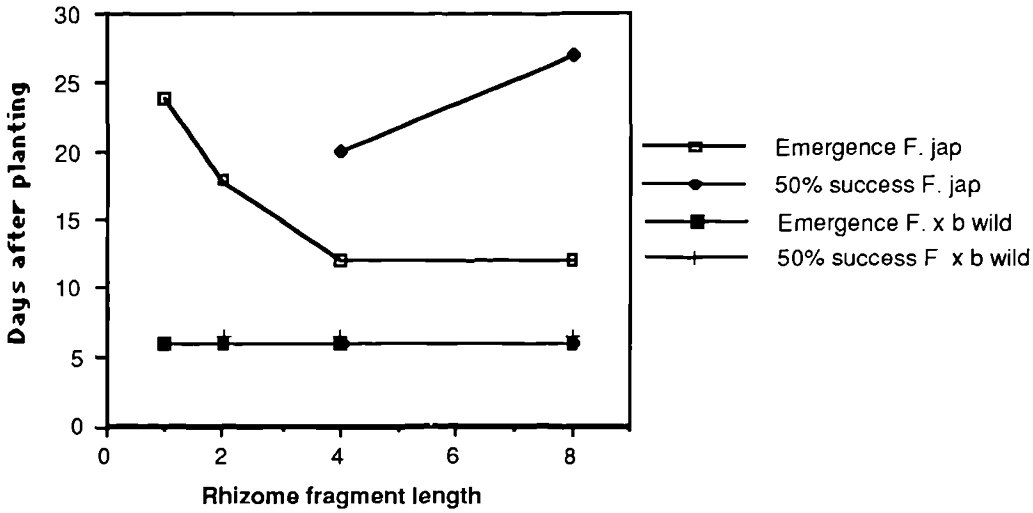


Figure 7.1 Relationship between rhizome fragment length, number of days to shoot emergence and days to achieve a 50% regeneration success rate for *F. japonica* and wild *F.* x *bohemica*. (50% regeneration success was not achieved within 30 days for *F. japonica* 1 cm or 2 cm rhizome lengths or *F.* x *bohemica* 1 cm rhizome lengths)

The results of these trials have shown that the optimum size of *F. japonica* rhizome fragment for rapid shoot development is 4 cm in length Adachi *et al.*, (1996b) described apical dominance as an inhibiting factor on rhizome bud development in intact rhizomes, where only terminal rhizome buds and winter buds at the base of stems normally produce shoots. It is suggested that in these studies, as fragmentation of rhizomes occurred, this apical inhibition was broken which encouraged shoot emergence from otherwise dormant buds. As fragment length increased, it is suggested that the effects of apical dominance were observed, delaying bud development and subsequent shoot emergence in longer rhizome fragments.

Once emerged, shoots produced by all fragment lengths continued to increase in height throughout the trial indicating successful establishment. A positive relationship was observed between shoot height and fragment size with longer fragment lengths producing taller shoots over the trial period than small fragments. A relationship between rhizome nutrient reserves and shoot production is suggested, with longer fragments sustaining taller shoots. Both Locandro (1973) and Dock Gustavsson (1997) reported a relationship between rhizome reserves and subsequent shoot growth, the former in *F. japonica* in the USA and the latter in *Cirsium arvense*. Depth of planting had a significant effect on rate of regeneration, with deeper planting of rhizome fragments resulting in less reliable shoot emergence due to nutrient reserves being utilised for shoot elongation up to the soil surface. In the context of the management of *Fallopia* species, the high invasive potential of rhizomes appears to be enhanced by fragmentation. Current guidelines (Welsh Development Agency, 1998a; 1998b) suggested that for disposal of *F. japonica* rhizome material, burial in landfill or on site should be at a depth of at least 2 m. Previous guidelines had suggested burial to 5 - 10 m deep (Welsh Development Agency, 1994). The depth of burial should ensure that even large mature rhizome fragments will not have sufficient reserves to produce shoots which will reach the soil surface. Sukopp and Starfinger (1995) reported that *F. sachalinensis* rapidly recolonised volcanic deposits due to the rapid regeneration of rhizome material which had been buried to a depth of 0.5 - 1.0 m following the 1977 and 1978 eruptions of Mt. Uso, on Hokkaido, Japan. The results of the current trials suggest that *F. japonica* has a greater invasion potential than *F. sachalinensis*. Depth of burial during disposal is therefore critical in preventing viable shoot production.

Adachi *et al.*, (1996c) observed that in undisturbed patches of *F. japonica* the rhizome system is physiologically integrated. Experiments undertaken on *F. japonica* var. *compacta* (the dwarf variety of the plant found on the high altitude volcanic deserts of Mt. Fuji) showed that severing the rhizome system within established patches of the plant with a sharp spade and allowing the patches to continue to grow without further disturbance had a negative effect on plant growth, reducing flowering within these patches to almost zero by the end of the growing season. A complete fertiliser was applied to a duplicate set of patches which continued to grow normally. Adachi *et al.* suggested that nitrogen is translocated from older rhizomes in the centre of a patch to the 'pioneer' stems on the perimeter. Photosynthetic products are translocated from these more sparsely arranged stems on the edge of the patch where light availability is high, to rhizome in the central area where stems are subject to lower light levels due to the shading effect of mature stems. In this way, continued expansion of the patch is supported by physiological rhizome integrity. It is possible that some of the differences observed in shoot regeneration success in the present trials between rhizomes of the same plant type and length are due to the position of the rhizome within the plant patch. Regeneration potential may differ according to rhizome position within the patch occupied by the plant. This could be researched further to aid an understanding of the expansion of the plant at individual sites.

The results of these trials indicate that the response of *F. japonica* to disturbance of rhizomes is to initiate shoot growth. In the context of control of the plant, the results of Chapter 5 have shown that a combination of digging followed by a single herbicide application results in a more effective level of control than a single herbicide application alone. The branching pattern of rhizomes, controlled by apical dominance as described by Adachi *et al.*, (1996b), suggests that for intact rhizome systems there are large areas of rhizome which at any one time are not actively producing shoots. What Adachi describes as 'daughter branches' are only stimulated when clumps of stems or crowns (see Figure 5.1) have produced shoots for longer than 5 - 10 years. By fragmenting these dormant rhizome sections, the apical dominance is broken with the result that buds are stimulated into growth. The disturbance due to digging on the trial plots in these studies resulted in significant increase in stem density with a corresponding increase in leaf area. This increase in leaf area allows for a more efficient uptake of herbicide and translocation to individual rhizome fragments resulting in improved levels of control. Clearly, the importance of putting in place restrictive practices on soil movement at or from an infested site without follow up herbicide treatment is underlined by these results. The policies being implemented by the City and County of Swansea, for example creating 'knotweed alert maps' for planning permissions, are vital in preventing the future spread of this species during site development.

Stem regeneration

This study has shown that cut stems of *F. japonica* and its hybrids have a high invasive potential (Chapter 2 and Chapter 4). Stem nodes from all sections of *F. japonica* stem, upper, middle and lower, were capable of regeneration in both an aquatic and terrestrial medium (Figure 7.2). The time required for shoot emergence and the time to achieve 50% regeneration success rate was more rapid for water sun treatments than for water shade or buried treatments indicating that regeneration of stem material in water could provide an effective means of dispersal to new sites in riparian habitats. Buried treatments did not achieve a 50% success rate suggesting that water and light availability are pre-requisites for successful stem regeneration. In water treatments, it is suggested that a more rapid emergence of shoots may have been due to a hormone response with more rapid leaching of hormones responsible for apical dominance in water treatments than in buried treatments.

A more rapid regeneration response was recorded for stems subjected to full sun treatment than was observed for those in shade indicating a response to light levels. Beerling (1991b) and Beerling *et al.* (1994) showed that growth and abundance of *F. japonica* were depressed on sites with low light availability and in greenhouse trials, Seiger (1993) confirmed that growth levels were lower under low light levels than those recorded for plants grown in full light. Reciprocal transplant experiments of *F. japonica* in the USA showed that survival and growth were significantly lower in forest understorey than on open streambanks. These differences were found to correlate with light availability (Seiger, 1997).

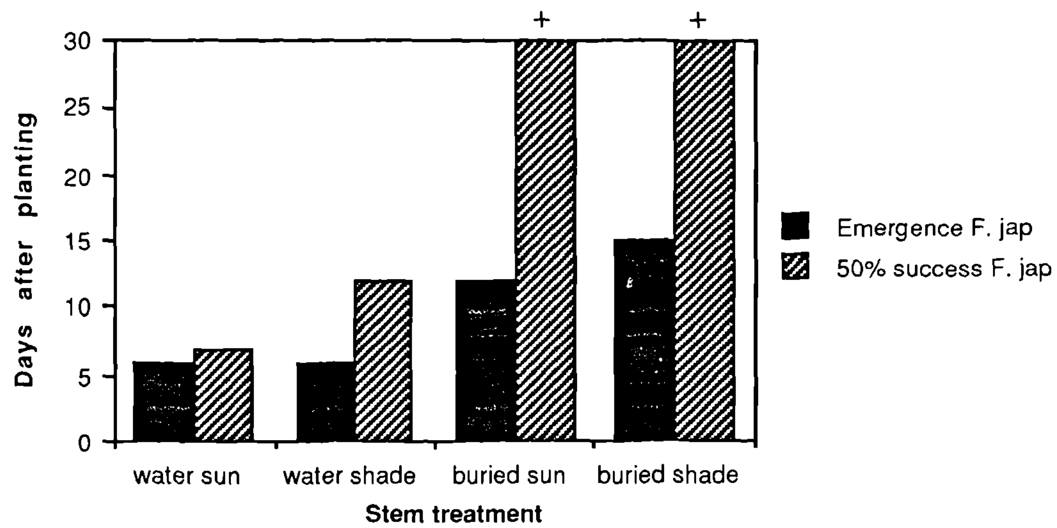


Figure 7.2 Comparison of number of days to shoot emergence and days to achieve a 50% regeneration success rate for *F. japonica* stems subjected to different environmental conditions. (+ indicates failure to achieve 50% regeneration success within 30 days)

Using the results of the studies in Chapter 4, a comparison of shoot regeneration from stems of different plant types shows that given the environmental conditions best suited to shoot initiation (water sun treatment), the number of days to shoot emergence was the same for stems from all plant types (Figure 7.3). However, in assessing the time required to achieve a 50% regeneration success rate, only wild hybrid plant material compares favourably with *F. japonica*. This confirms results found for wild hybrid rhizome material. Hybrid male and female plants from Buckingham Palace Gardens achieved this rate by 13 and 17 days respectively as did *F. sachalinensis* but *F. japonica* var. *compacta* failed to achieve this success rate by the end of the trial.

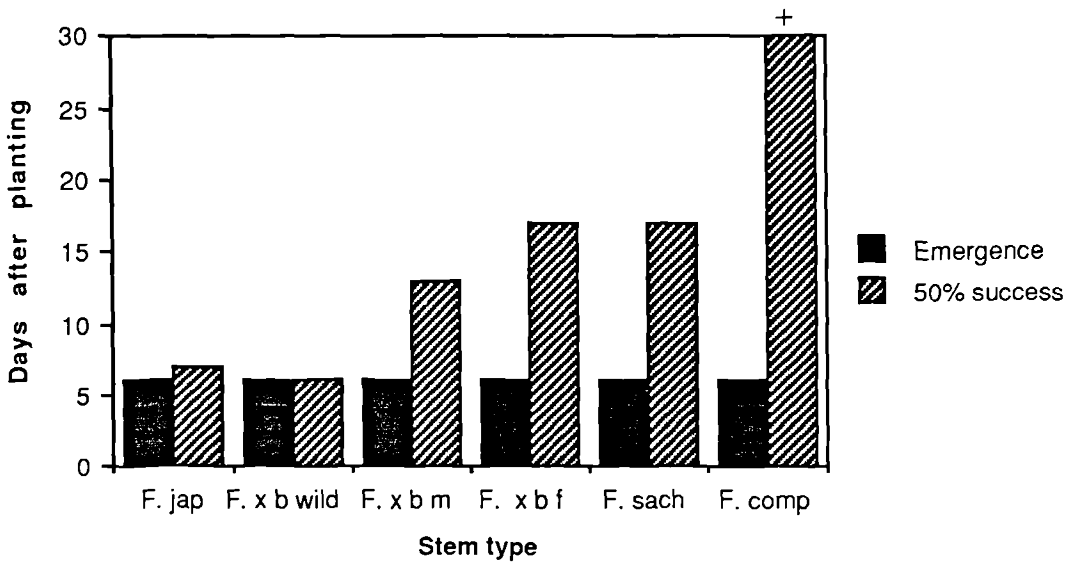


Figure 7.3 Comparison of number of days to shoot emergence and days to achieve a 50% success rate for stems from different plant types subjected to a water sun treatment. (+ indicates failure to achieve 50% regeneration success within 30 days)

The relative invasive potential of each of these species by vegetative propagation has been verified by the results obtained during these studies. *F. japonica* with the exception of the wild hybrid material is clearly the most successful invader given the criteria of a high probability of regeneration success and rapid shoot emergence. *F.* x *bohemica* male and female plants from Buckingham Palace required a longer time to achieve the same level of success but have been shown in these studies to regenerate successfully from both stem and rhizome fragments. *F sachalinensis* and *F. japonica* var. *compacta* do regenerate from vegetative propagules but with comparatively lower probability of success.

The discovery of successful vegetative regeneration of hybrid material has important implications for the future management of this group of species. If the vegetative regeneration rates for hybrids are comparable to that of *F. japonica* the rate at which the distribution of hybrid plants increases could follow a similar pattern to that of *F. japonica* early this century. This work has identified the need for implementation of strategic management policies such as those proposed in Chapter 6, to prevent the continued expansion of not only *F. japonica* but also *F.* x *bohemica via* vegetative spread.

F. x *bohemica* has only been identified as a naturalised species for just over a decade, therefore the invasion of hybrids in the British Isles is still at an early stage in the invasion process (compare with Figure 1.6 for *F. japonica*). For *F. japonica*, the time lag between first record of naturalisation and the beginning of exponential growth was approximately 50 years. The invasion of *F.* x *bohemica* is still in what Conolly (1977) describes as its pioneer phase between naturalisation and exponential increase in distribution. If prediction of invasion is possible, given the plant's characteristics shown in these studies, *F.* x *bohemica* surely fits the description of a seriously successful invader. In the light of experience of the successful invasion of *F. japonica* by purely vegetative spread, the results obtained in these regeneration studies indicate that *F.* x *bohemica* is at least if not more invasive. In particular, an increase in male-fertile hybrid plants has serious implications in terms of the potential for future sexual reproduction within this group of *Fallopia* species.

7.3 GENETIC VARIABILITY

In its native geographic range, Japan, Taiwan and northern China, the genetic constitution of *F. japonica* and related species is diverse, primarily due to sexual reproduction but also due to the presence of a number of different forms. Whereas in the British Isles, *F. japonica* is male-sterile, in Japan, both male and female forms exist, in addition to a number of sub-species and varieties (Ohwi, 1965). Morphologically *F. japonica* plants in Europe differ from those observed in Japan (Sukopp and Sukopp, 1988; Bailey, 1997). *F. japonica* in the British Isles is a much larger plant which has a more aggressive habit than Japanese plants (Adachi pers.

comm.). Certainly, there is a more varied range of plants in Japan with both male and female forms, morphological differences in flower colour, leaf shape and size, ecotypes specific to different altitudinal ranges and differences in the genetic constitution of plants primarily in terms of ploidy level (multiples of chromosome number). Clearly the range of plants observed in the British Isles do not reflect the full extent of variation in these species in their native range. Hooker's illustrations of 1880 clearly show a male-sterile specimen of *F. japonica* and research undertaken to date has confirmed the suggestion that for *F. japonica* at least, a clonal population of male-sterile plants exists in the British Isles (Beerling *et al.*, 1994; Bailey, 1994; Bailey *et al.* 1996).

This study (Chapter 3) has shown that in addition to the parental species *F. japonica*, *F. sachalinensis* and *F. japonica* var. *compacta*, the hybrid *F.* x *bohemica* (a cross between male-sterile *F. japonica* and male-fertile *F. sachalinensis* or *F. japonica* var. *compacta*) is well established throughout the British Isles. Four types of *F.* x *bohemica* hybrids have been established as being present in British populations, these are both male and female plants of chromosome number 2n = 44 and 2n = 66. By morphological study of leaf characteristics and cytological study of chromosome numbers, the preponderance of these hybrids in the British Isles have been shown in this study to be hexaploid (2n = 66) and male-fertile (78% and 73% of those records analysed respectively). There is potential for further hybridisation in this group of species as hybrid plants are often recorded in close proximity to parental species as at the Cirencester study sites (Chapter 3). Back-crosses between *F.* x *bohemica* 2n = 44 plants and *F. japonica*, *F. sachalinensis* or *F. japonica* var. *compacta* are relatively straight forward in terms of the pollen fertility of tetraploid hybrids (2n = 44) and regularity of meiosis (pairing of chromosomes during the fertilisation process) (Bailey, 1997) (Table 3.8). Despite hexaploid hybrids (2n = 66) having been shown to have low pollen fertility and irregular meiosis (inefficient pairing of chromosomes during the fertilisation process), it would still be possible to achieve *F.* x *bohemica* x *F. japonica* back-crosses due to the high numbers of flowers produced and lack of competition from *F. japonica* pollen. In fact mixed parentage is possible in seeds collected from a single plant due to the range of pollen providers which have now been identified in the British Isles (Bailey, 1997).

The hybridisation process is not yet fully understood and it is possible that hybrid plants were inadvertently introduced to the British Isles along with *F. japonica*, *F.*

sachalinensis and *F. japonica* var. *compacta*. It is also possible that the hybrid has arisen naturally by seed as both male-fertile *F. sachalinensis* and male-fertile *F. japonica* var. *compacta* are present in the British Isles. However, genetic analysis of seed set on *F. japonica* has shown that the majority of seeds are of hybrid origin but are not of the constitution *F.* x *bohemica*. Seed material is invariably the result of pollination by *F. baldschuanica* (Russian vine) another related *Fallopia* species. Although this seed is viable under laboratory conditions, only one plant of this constitution has been recorded in the wild in the British Isles (Bailey, 1992).

Seed dispersal plays a major role in the dispersal of *F. japonica* in its native range. Maruta (1976; 1983; 1994) describes factors affecting seedling growth and establishment in the volcanic deserts of Mt. Fuji. She reported a critical size below which seedlings would not survive to the following growing season. This size was determined by altitudinal factors influencing the length of growing season. A 63% survival rate was observed for seedlings at 1,400 m whereas only 3% survived at 2,500m. Seedlings at 1,400 m which had achieved a dry weight of at least 40 mg by the end of the growing season showed a 100% survival rate to the next year (Maruta, 1983). Maruta (1994) suggested that the *P. cuspidatum* on Mt. Fuji (syn *F. japonica* var. *compacta*) is an alpine ecotype of a lowland species which is unable to maintain seedling establishment at altitudes above 2,500 m due to its relatively small seeds whereas the large-seeded characteristic of the related species *Polygonum weyrichii* may be an adaptive feature leading to its successful seedling establishment at higher altitudes. The conditions on Mt. Fuji are harsh, with slopes covered by snow from mid December to late March at 1,400 m and November to late April at 2,500 m and mean minimum temperatures reaching -14 and -19°C respectively. Water and nutrient holding capacity of the basaltic gravels is low despite high mean annual precipitation (4,849 mm). Nevertheless, seedlings which germinated in early May had reached a mean root length of 6 cm by early July, seedlings which germinated in June had roots measuring less than 4 cm. The major cause of seedling mortality during the growing season was early summer drought. Seedlings which had germinated in May were able to tolerate the drought conditions due to longer and more developed root systems whereas those which did not germinate until June died (Maruta, 1976). Certainly climatic conditions in the British Isles are not as severe as those in which seedlings clearly survive in the native range of the plant. However, the genetic constitution of plants in Japan has been observed to be much more varied than that of plants in the British Isles and this could have an influence on seedling survival.

Seed viability from *F. japonica* has been studied in other introduced geographic ranges of the plant. In the USA where both male and female plants of *F. japonica* are reported to exist, to date, seedlings have not been recorded as surviving in the wild (Locandro 1973; 1978; Seiger 1993; 1997). Seiger (1997) reported that seedlings germinated and grown under laboratory conditions were morphologically similar to *F. japonica* x *F. baldschuanica* hybrids. In Central Europe however, a more complex situation is observed. The variation in hybrid forms is greater than that observed in the British Isles with the addition of male-fertile and male-sterile *F. x bohemica* plants with chromosome number 2n = 88 (Bailey, 1997). The male-fertile octoploid hybrid has the potential to act as a substitute for male-fertile *F. japonica* as a pollen provider. Alberternst (1995) described seedlings surviving along the River Wolfach in south west Germany from 1994 to the following year and suggested that the range of different morphological features observed in plants along the river indicated successful distribution by seed in this region.

There is therefore a unique situation in the British Isles regarding the genetic constitution of this group of *Fallopia* species. *F. japonica* exists as only male-sterile plants and is expected to be clonal. *F. sachalinensis*, *F. japonica* var. *compacta* and *F. baldschuanica* exist as male-fertile and male-sterile plants. The hybrid *F.* x *bohemica* exists as male-fertile and male-sterile plants at two ploidy levels (2n = 44 and 2n = 66). *F. japonica* sets seed but the majority of seed so far examined has been shown to be hybrid in origin with *F. baldschuanica* and seed viability in the wild, in the British Isles at least, is low to non-existent.

The potential for viable seed to be produced at some time in the future by one or other of the above hybridisation routes has to be addressed as a strong possibility. There is ample opportunity for viable pollen to be produced by any of the male-fertile congeners and the extent of seed-set observed in *F. japonica* suggests that hybridisation is happening.

The implications of this group of species spreading by seed in terms of management of the plant are at present not severe. However, the hybrid form of the plant has only been known for just over a decade and what is now being observed is a much wider distribution of hybrid plants with a much greater genetic variability than was first thought existed. If at some time in the future a genetic combination occurs from which viable seeds are produced which are able to establish and survive in the wild, as has been reported in Germany (Alberternst, 1995), this would add a new dimension to the future management of the plant. As seeds from these species are wind dispersed, natural means of dispersal would no longer be associated purely with water courses and restrictions for example on soil movement which are effective in preventing spread by anthropogenic activity would become less effective. The habitats suffering the most severe invasion of *F. japonica* have been identified in this study (Chapter 6) as those which are subject to disturbance such as water courses and waste ground in urban areas where human activity has been responsible for spread. With the advent of seed dispersal as a potential means of further spread, even greater distribution of *F. japonica* congeners could be expected than that seen for *F. japonica*. Kowarik (1995a) described the time lags observed between introduction of a species and its subsequent invasion. With *F. japonica*, the time between first date of naturalisation and the present has been just over one hundred years. *F.* x *bohemica* has only been observed as a naturalised species in the British Isles for just over a decade and at present is only known from 131 locations (Chapter 3). The vegetative dispersal potential of these plants has been addressed in this study (Chapter 4) and results indicate a comparable potential for vegetative spread to that of *F. japonica*. There is therefore potential for an exponential increase in *F.* x *bohemica* plants by purely vegetative spread over the next few decades. As the greater majority of hybrid plants examined during this study have been identified as male-fertile, the potential for a sexual explosion in this group of species in the British Isles is apparent.

7.4 CONTROL AND MANAGEMENT

The management of *Fallopia* species is discussed in relation to two main habitat types. Firstly management in riparian habitats where dispersal is regulated by natural processes and secondly in terrestrial habitats where dispersal is reliant on human activities.

Riparian habitats

In riparian areas, *F. japonica* grows along stream and river banks and is susceptible to dispersal by rhizome fragmentation during high water flows. It has been demonstrated in this study (Chapter 2) that small fragments of rhizome measuring one centimetre in length and weighing as little as 0.7 g are capable of successful regeneration. Fragments of rhizome washed downstream and deposited on floodplains produce shoots from previously dormant buds on the rhizome surface. Once *F. japonica* is present within a river catchment, this natural means of dispersal ensures effective transport of the plant to sites downstream. In this respect, the invasion of *F. japonica* mimics that of aquatic plants e.g. *Acorus calamus, Elodea canadensis* (Anon, 1982) and *Crassula helmsii*, (Dawson, 1994) relying on a combination of vegetative propagules and water transportation to reach new sites. In addition, the level of disturbance in riparian areas ensures that open sites are available for the establishment of these propagules. Pysek (1997) confirmed this trait when looking at the proportion of alien clonal plants in wetlands (70%) and aquatic habitats (100%) in South Africa and New Zealand respectively.

Control programmes in riparian habitats can be thwarted by natural events such as flooding where chemically treated rhizome material can be washed downstream before the end of the treatment programme resulting in the establishment of new plants. This has been observed in the River Conwy catchment in Wales where a 3 year control programme has been hampered by flooding (Lane, pers. comm.). Considering the length of time required for a conventional herbicide control programme using glyphosate or 2,4-D amine (3 - 5 years), the risk of disruption to control programmes is high, particularly in river systems prone to flooding. The need for continued monitoring and assessment of plant distribution is therefore vital to ensure that new infestations are added to ongoing control programmes. The use of management tools such as GIS (Chapter 5) could assist in this process by identifying areas of river catchments at risk of flooding and collating these data with *F. japonica* distribution and existing or proposed control programmes.

Control techniques for *F. japonica* can in themselves provide potential dispersal routes and enhance further spread of the plant. Cut stems washed or blown into watercourses provide a source of regenerative material. This study has shown that the combination of an aquatic environment and high light availability provide the environmental conditions required for both rapid and successful regeneration of stem material. Careful disposal of stem material following cutting or mowing *F. japonica* near to watercourses is therefore vital in order to prevent further spread.

Non -riparian habitats

Dispersal of clonal propagules in non-riparian habitats relies on human activity for transportation. The dispersal of *F. japonica* throughout urban and rural areas through roadside tipping of garden waste, soil transportation from infested sites and disturbance at or near to infestations of *F. japonica* has been a major factor in its spread. The results of this study (Chapter 2) have shown that small fragments of rhizome gave a high regeneration success when planted in a soil medium. Cut stems buried in a soil medium were also capable of regeneration but took longer to produce shoots. However, the rate of root production observed from planted stems was greater than that for stems in an aquatic medium suggesting that once shoots had been produced, establishment and subsequent growth of plants would be supported by the root system. All parts of the plant stem were capable of regeneration and shoots were recorded from both nodes for lower, middle and upper stem segments indicating a high invasion potential for all vegetative plant parts. Disposal of vegetative material of *F. japonica* has been a particular problem in urban areas with fly tipping of garden waste on road verges and waste ground. The results of the Swansea survey (Chapter 6) clearly show that waste ground is the single largest landuse type infested with *F. japonica* in the city of Swansea. Awareness raising of the risks of spreading the plant through articles in the local newspaper, leaflets produced by government agencies, radio and television reports need to be directed at the general public. Contractors dealing with, for example, landscaping works, weed control and highway maintenance need to be educated in the proper disposal of both stem and rhizome material in order to prevent further spread.

It is clear from this study that control measures available for other invasive alien species are limited in their use for *F. japonica*. This is primarily due to the structure of the plant. Cutting, burning, grazing and shading are limited in their effectiveness as they target only the above ground growth of the plant. Although repeated cutting or removal of top growth may reduce the vigour of the plant by reducing rhizome resources, on established stands, the time required to achieve effective control is measured in years. There is also a risk (Beerling, 1990a) that cutting encourages lateral growth. Seiger and Merchant (1997) recommended that four cuts of the plant during the year would result in a net depletion of rhizome biomass but suggested that it is unlikely that *F. japonica* could be eradicated by cutting alone. Cutting also produces waste stem material which potentially increases the risk of vegetative regeneration particularly if cut material is allowed to reach water courses or is buried in damp conditions.

Digging has been shown in this study to increase stem density (Chapter 6) and is effective as a control method only if followed by treatment with a translocated herbicide. Translocated herbicides provide the most effective method of targeting the rhizome system. In riparian areas, the effective herbicides available are limited by legislation to glyphosate and 2,4, D-amine (Roblin, 1988; Beerling, 1990a; 1990b; Child *et al.*, 1992; de Waal, 1995). In non-riparian areas, persistent herbicides such as triclopyr, picloram and imazapyr have been shown to be effective (Scott and Marrs, 1984; Child *et al.*, 1992). There are few techniques which are truly effective and, of those which are, application is required over a significant length of time in order to achieve success. The results of trials (Chapter 5) which combined digging and spraying using the regeneration potential of the plant to increase the above to below ground biomass ratio of the plant have shown that such disturbance enhances the effect of glyphosate. Gritten (1995) suggested that, with *Rhododendron ponticum*, effective control is only achieved when herbicide is applied to all leaves of the plant as lateral translocation is weak. Further research on the translocation properties of *F. japonica* rhizome will be necessary to aid the understanding of herbicide uptake in this plant.

The effective control and management of an invasive species requires an understanding of the ecology of the species, the use of the particular environment and an assessment of the resources available to deal with the plant both in terms of treatment methods and financial support (Kluge *et al.*, 1986; Groves, 1989; Navas, 1991; Hobbs and Humphries, 1994; Sheley *et al.*, 1995). In order to develop a successful management strategy for *F. japonica* in the British Isles, a range of management options need to be considered. The case study of the city of Swansea described in Chapter 6 indicates the approach necessary in order to tackle the problem of infestation from an organisational perspective. In a local authority such as Swansea, budgets are required, accurate assessment of the extent of the problem and an integration of the management of the plant into existing policy areas needs to be considered. An active programme of education, training and awareness raising is also needed in order to reduce the risks of further spread.

The use of GIS as a management tool aids this process by allowing spatial planning to ensure that further spread is halted, protection of vulnerable areas is achieved, effective control measures are undertaken and monitored and co-ordination is achieved between landowners, with the database facility providing the necessary information required to raise awareness at each stage of the management process. The failure of control strategies for invasive species is often due to a lack of long-term financial commitment (Gritten, 1995). An assessment of the costs involved in dealing with the infestation in just one local authority area in Wales demonstrates that the use of conventional control measures is not sustainable. In this study, the cost of eradicating 48 ha of *F. japonica* from 96 square kilometres in the city of Swansea using conventional treatment methods has been estimated at £0.4 million. This is in agreement with Gritten (1995) who gave an estimate of £45 million for control using conventional herbicide application of 3,400 ha of *Rhododendron ponticum* in Snowdonia National Park. Given these astronomical costs for conventional treatment methods, what is required is a long term, effective control programme which tackles the problem at an ecological level such as biological control. The costs of a biological control programme are favourable when compared to costs of conventional control methods for example, Shaw (1997) estimates the cost of a classical biological control programme for *F. japonica* in the British Isles to be in the region of £700,000.

7.5 FUTURE PROSPECTS

The idea of ecologically based management for invasive species is not new (Kluge *et al.* 1986; Groves, 1989; Navas, 1991; Hobbs and Humphries, 1994; Sheley *et al.*, 1995). The use of integrated control measures such as cutting and herbicide control, burning, ploughing, grazing may be appropriate to certain species in specific habitats. However, the results of this study suggest that an additional method is required for *F. japonica*. Whilst some progress has been made in refining available control measures (such as combined digging and herbicide treatments) the infestation of *F. japonica* in the British Isles is still increasing.

State-of-the-art treatment methods (Chapter 5), co-ordinated management strategies and the application of GIS (Chapter 6), all help towards a better and more efficient control of *F. japonica*. However, cost implications, access problems and the extent of the invasion in other areas in its introduced range, demand a more permanent method of control such as biological control. There is potential for the future control of *F. japonica* to be achieved by biological agents (Fowler and Schroeder, 1990; Fowler *et al.*, 1991; Holden *et al.*, 1992, Fowler & Holden, 1994). Such clonal plants have, in the past, made good candidates for biological control (S. Fowler, pers. comm.).

In Japan, *F. japonica* is regarded as an ordinary component of the vegetation, not typically a nuisance species, colonising volcanic fumaroles and open ground (Hirose & Kitajima, 1986). The species is much more vigorous and invasive in Europe due to the lack of a range of associated host specific insect herbivores and plant pathogens which attack and damage the plant in its native habitat. Zwoelfer (1973) records an apparently host specific leaf feeding Chrysomelid beetle, *Gallerucida nigromaculata* as playing a role in the natural control of *F. japonica* in Honshu, the largest of the four islands in Japan. Studies carried out to date have identified 16 species of invertebrate leaf feeders of *F. japonica* in Japan (Emery, 1983) and preliminary faunal surveys in 1991 carried out by entomologists at Yamaguchi University have produced a list of 40 insect species of 5 orders and 22 families which were collected or reared on *F. japonica* in Yamaguchi and associated prefectures in Japan (Fowler and Holden, 1994). Only tentative identifications have so far been available but most of these insects are herbivores and many belong to insect families that include specialist biocontrol agents used against target weeds in other parts of the world.

Emery (1983) identified 12 invertebrate species feeding on *F. japonica* in Wales, although many of these species have been shown to be polyphagous and not host specific to *F. japonica*. Zimmermann and Topp (1991a; 1991b) investigated the insect communities associated with *F.* x *bohemica* , *F. japonica* and *F. sachalinensis* in Central Europe and identified 4 insect species feeding and surviving on hybrid plants, two species feeding only on the hybrid plants and not on the parental species.

In addition to insect herbivores, an as yet unidentified fungal disease was reported as being highly damaging to *F. japonica* at all the sites surveyed in Yamaguchi (Fowler and Holden, 1994). Several other pathogens have been identified from *F. japonica* both in Japan and in the British Isles. The most promising potential pathogen to date has been identified from *ad hoc* collections of material from Japan made by the International Institute of Biological Control. These include a rust fungus *Puccinia polygoni-weyrichii* which is host specific to *F. japonica* in Japan; *Phyllosticta rayoutina; Puccinia polygonia-amphibii*; *Phoma* species (a leaf spot fungus) and

Colletotrichum gloeosporoides. At present too little is known to allow assessment of their potential as biological control agents although there is potential for certain pathogens can be developed as 'biological herbicides'. In the past, *C. gloeosporoides* sub species have been successfully developed under the trade name 'Collego' (Strobel, 1991).

A classical biological control programme would aim to introduce and establish specialised insect herbivores and/or plant pathogens from the native range of the plant to reduce and stabilise the plant at a sub-economic level. The programme would involve three main stages: firstly, collection and selection of potential agents in the country of origin, secondly, extensive host specificity trials to ensure the agent would not cause damage to related species or economically important crops, and thirdly, a culturing and quarantining procedure to ensure that the chosen agent was free from parasites and diseases (Holden *et al.*, 1992). These stages would probably be undertaken over a period of 3-5 years. The agent would only be released when all these stages have been completed successfully. Control of the plant would become effective over a number of years.

The dispersal abilities of the agent are usually adequate to reach most locations in which the target plant grows and control can be achieved in areas which would otherwise have remained untreatable due to access problems, particularly in difficult terrain. Biological control is environmentally very safe, providing the proper procedures are followed, with no harmful residues and no risk to humans or animals. By reducing the competitive advantage of the target plant, native vegetation can become re-established resulting in positive effects on the local flora. Further, classical biological control has the advantage that once the agents are successfully established, the control is permanent and little or no further expenditure on other forms of control is required. It is usually self perpetuating and requires no repeated applications in contrast to mechanical and herbicidal management strategies. The method relies on control of the plant by reduced vigour and spread rather than on eradication.

Biological control has been used successfully elsewhere in the world to control other nuisance plants such as *Chondrilla juncea* and *Optunia* spp. (Fowler *et al.*, 1991). However, management strategies which promote awareness, prevent further spread and reintroduction and integrate existing methods of control will still be needed whilst biological control is developed.

7.6 SUMMARY

The success of the invasion of *F. japonica* throughout the British Isles is due not only to the plant's characteristics but to an interaction between the plant and its environment, including the impact of human activity. The rapid growth rate of the plant, its high regenerative ability from small fragments of vegetative material and tolerance of adverse conditions in combination with its highly competitive ability are aspects which make the plant a successful invader. The anthropogenic influence of disturbance through soil cartage into sites previously not infested has effectively 'planted' *F. japonica* throughout the British Isles. The invasion capability of *F. japonica* is equivalent to 20 million potential propagules of *F. japonica* rhizome per hectare (estimated on the basis of 14,000 kg ha^{-1} underground biomass x 0.7 g smallest rhizome fragment to successfully regenerate (Brock, 1994; Brock *et al.*, 1995). When this high level of invasion potential is added to the lack of management of the plant allowing it to become established in 'safe sites' it is not difficult to see how in just over 100 years, *F. japonica* has become one of the most successful plant introductions to the British Isles.

Whilst this accounts for the success of the species it does not, in itself provide the basis for management. There arise from this study four key features of *F. japonica* in relation to its future management:

- the role played in the dispersal of the plant by stem and rhizome material
- the structure of the plant in relation to finding effective methods of control
- the potential for further expansion by sexual reproduction associated with an increase in the distribution of hybrid plants
- the continued need for accurate assessment and monitoring of its distribution.

F. japonica is not alone in presenting problems to land managers in the British Isles (Cronk and Fuller, 1995). There are many aquatic and terrestrial plants which are already established or are becoming nuisance species in the British Isles. These include well established invaders originally introduced as ornamental plants such as *Heracleum mantegazzianum* (Caffrey, 1994; Tiley *et al.*, 1996; Tiley and Philp, 1997; Wade *et al.* 1997) *Impatiens glandulifera* (Beerling, 1990a; Beerling and Perrins, 1993) and *Rhododendron ponticum* (Thomson *et al.*, 1993; Gritten, 1990; 1995), *Crassula helmsii* (Dawson and Henville, 1991; Dawson, 1994; Child and Spencer-Jones, 1995) *Azolla filiculoides* (Janes, 1995) and more recently, *Hydrocotyle ranunculoides* (Centre for Aquatic Plant Management, 1997).

Many of the above species cause significant environmental problems and the management principles described in this study would be applicable to these invasions. What has been shown is that without placing the control of a species into the context of land management strategies, protection of vulnerable areas and prevention of future invasions can never be achieved. An integrated approach which considers not only the biology, ecology and control of the species but also considers the role which human factors play in an invasion must form the basis of future decision making in invasion management.

7.7 EXECUTIVE SUMMARY

- *Fallopia japonica*, an introduced ornamental plant native to Japan and SE Asia is continuing to expand its distribution in the British Isles despite efforts to control it. The spread of the plant is enhanced in riparian habitats by fragmentation of plant parts during high water flows and in other environments by anthropogenic activities including the cartage of soil contaminated with plant fragments.

- In greenhouse trials of above and below ground material, the regeneration of *F. japonica* rhizome material was rapid with shoots produced from 4 cm fragments 12 days after planting and sustained for at least 30 days. Increasing length of rhizome produced progressively taller shoots indicating a relationship between rhizome reserves and subsequent growth potential. Further research is necessary to determine the regulatory mechanisms which determine bud development and shoot production in intact and fragmented rhizomes. Regeneration of stem material in an aquatic medium gave a more rapid response to shoot production than stems buried in a soil medium (6 days and up to 42 days respectively) with buried stems producing a greater percentage of roots and greater shoot height than stems in an aquatic medium. The position of stem node on the plant did not significantly influence the potential to produce shoots.

- Hybridisation of *F. japonica* with related species in the *Fallopia* genus has resulted in a genetically diverse population of hybrid plants and seed. Whereas all *F. japonica* in Britain is male-sterile and is unable to produce true *F. japonica* seed, there is evidence that hybrid seed is set. Although its origin is not clear, the hybrid *F.* x *bohemica* is now present in 131 localities in the British Isles. Hybrid seed is viable under laboratory conditions but seedling survival in the field has not yet been observed. Further work is necessary to determine the conditions required for seedling survival and to document the genetic variability within hybrid populations.

- The regeneration potential of hybrid *F.* x *bohemica* material was studied under greenhouse conditions. Regeneration from rhizome fragments indicated that a mean fresh weight of 0.9 g of hybrid rhizome material was sufficient to form a new plant. This is comparable with earlier studies for *F. japonica* where a mean fresh weight of 0.7 g was required. Stem material achieved higher regeneration rates when subjected to buried treatments than those in an aquatic medium although neither treatment exceeded the regeneration rates for *F. japonica*. Regeneration rates for *F. sachalinensis* and *F. japonica* var. *compacta* were lower than *F. japonica* in terms of percentage regeneration success, time to shoot production and height of shoots. However, each of these species are capable of vegetative regeneration from fragments of either above or below ground tissue.

- In field trials, disturbance by digging to the full depth extent of rhizomes to ensure thorough rhizome fragmentation resulted in a 200% increase in stem density when compared to control plots. A combination of digging in autumn followed by application of glyphosate as a foliar spray the following spring resulted in an improved level of control one year after application compared to spraying alone (93% kill and 25% kill respectively). This combination of treatments would be suitable for brown field sites prior to development where rapid control is required.

- An integrated management stragtegy for *F. japonica* was explored through a case study of the city of Swansea. The use of accurate survey methods and comprehensive data storage facilities such as GIS has improved the ability to link anthropogenic activities in the urban environment with the distribution of the plant. These links have enabled control methods and management practices to be selected on a site by site basis and have allowed priorities for treatment to be defined and implemented through the planning process.

- Without co-ordination of activities of the various bodies currently dealing with the plant and a thorough understanding of the modes of spread and dispersal of *F. japonica* and its congeners, these plants will continue their invasion. Management practice which is geared to prevention of spread and protection of vulnerable habitats is required.

- Further research is indicated in order to increase the understanding of factors affecting hybrid seedling viability and improving methods of control including refining conventional treatments whilst exploring the potential for biological control.

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APPENDIX ONE

The International Centre of Landscape Ecology (ICOLE) is currently carrying out research into various aspects of the ecology, control and distribution of *Fallopia japonica* var. *japonica*.

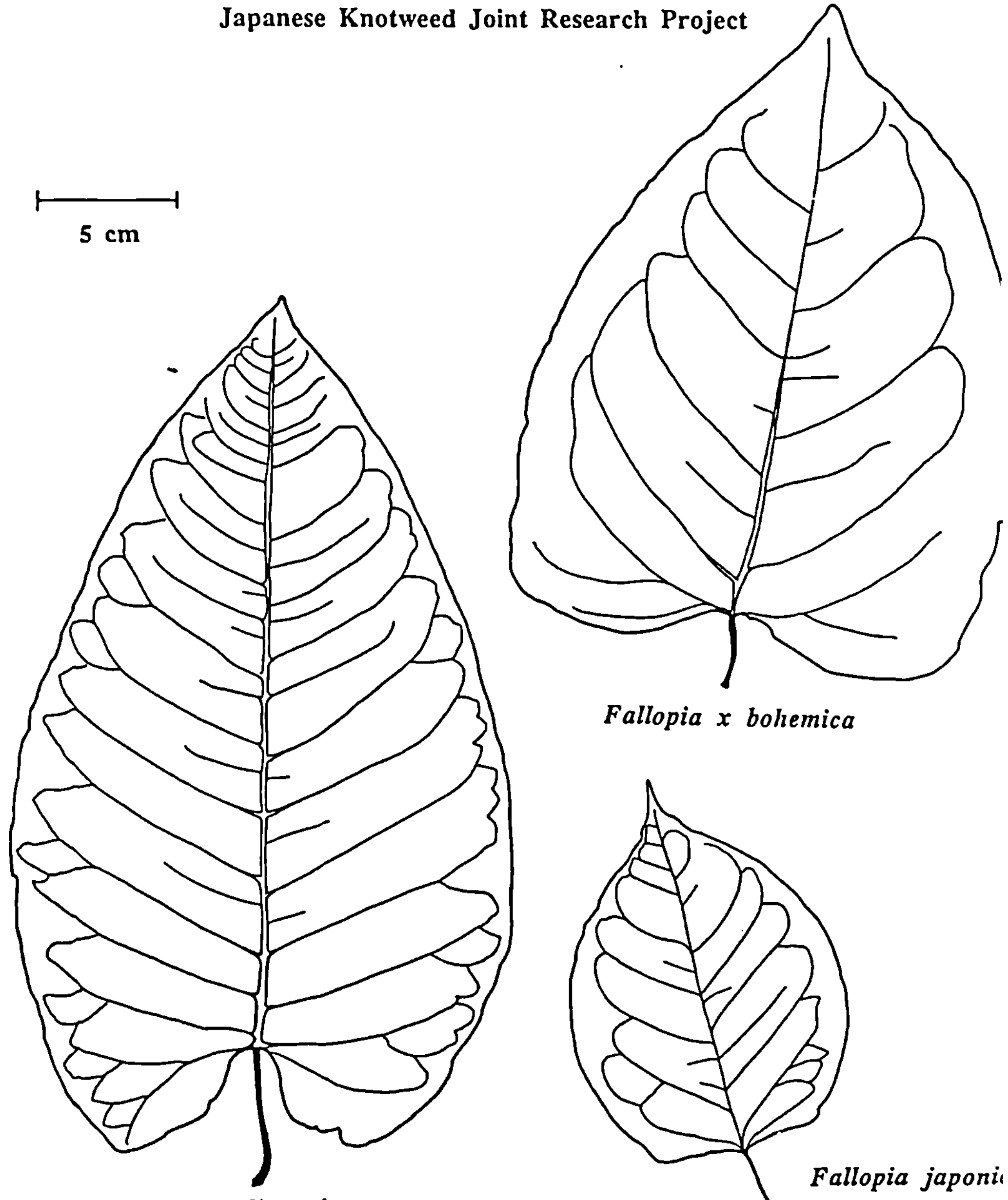
A leaflet "Guidelines for the control and management of Japanese Knotweed (*Fallopia japonica*)" will be available early in 1993, produced by ICOLE in collaboration with National Rivers Authority.

For further details contact ICOLE at the address overleaf.

JAPANESE KNOTWEED HYBRID SURVEY

Leicester and Loughborough Universities

Japanese Knotweed Joint Research Project



Fallopia sachalinensis

Fallopia x bohemica

Fallopia japonica var. japonica

THE PROJECT

The Leicester and Loughborough Universities Japanese Knotweed Joint Research Project is being carried out by the Department of Botany at Leicester University and the International Centre of Landscape Ecology at Loughborough University. This joint project has been initiated to discover the extent of genetic variability within the population of Japanese Knotweed and to assess the distribution and invasion potential of the hybrid *Fallopia* x *bohemica* in the British Isles.

We are currently compiling a distribution map of *Fallopia* x *bohemica* and would appreciate your help in sending us details of any hybrids which you may have seen.

IDENTIFICATION KEY (see illustrations)

Fallopia sachalinensis (F. Schmidt ex Maxim.) Ronse Decraene	***Fallopia japonica* var. *japonica*** Syn. *Reynoutria japonica* (Houtt.) Ronse Decraene	***Fallopia* x *bohemica*** (*F. sachalinensis* x *F. japonica*) (Chrtek & Chrtkova) J. Bailey
2n = 44	2n = 88	2n = 66, 44
Striking, gigantic plant to 4m	Large plant to 2-3m	Habit intermediate 2.5 - 4m tall
Leaf Size/Character: Basal leaves ovate to oblong, base cordate; up to 40 x 22 cm, length:width ratio *c.* 1.5; Undersides of leaves with scattered, long, flexuous hairs (trichomes)	**Leaf Size/Character:** Leaves ovate, acuminate, base truncate; 10-15 cm long, length:width ratio 1-1.5; Undersides of leaves entirely glabrous	**Leaf Size/Character:** Leaves intermediate in size and shape, weakly to moderately cordate at base, tip acuminate; up to 23 x19 cm, length:width ratio 1.1-1.8; Undersides of larger leaves with numerous short, stout hairs (trichomes), (easily visible with a hand lens)
Male-fertile flowers (with exserted anthers) and male-sterile flowers (with small, empty included anthers and well developed stigmas) borne on separate plants	Flowers usually male-sterile	Male-fertile and male-sterile flowers borne on separate plants

FALLOPIA X BOHEMICA

- **The most reliable characters for the identification of hybrids are: leaf shape, leaf size and trichome (hair) types**
- **It is important that only fully mature lower leaves are used** as early season leaves and leaves from the upper part of the plant are very variable and are of little use for identification purposes
- **Male-fertile plants are invariably hybrid in the British Isles**
- **Absence of good seed set is not a sign of hybridity in this genus**

HYBRID SURVEY - REQUEST FOR HELP

Please use this leaflet to help you identify the hybrid, fill in the slip below and return it, preferably before 31st May 1993, to:

Lois Child, ICOLE, Loughborough University, Loughborough, Leics. LE11 3TU or
Dr. John Bailey, Dept. of Botany, University of Leicester, Leicester, LE1 7TH

Please estimate the area covered by the stand(s) and include a typical leaf for verification.

Thank you for your assistance.

JAPANESE KNOTWEED HYBRID SURVEY

Date ____________________

Hybrid form ____________________

Location ____________________

Vice County ____________________

O.S.Grid Reference ____________________

Recorded by ____________________

Address ____________________

____

____

HDRA/94/Mem.Exp.4

JAPANESE KNOTWEED HYBRID SURVEY

Firstly, thank you very much for offering your assistance.

Check list: Instructions on how to take a National Grid Reference- 'Using the National Grid'.
Instructions and Record sheet (Early summer)
Instructions and Record sheet (Late summer)

Important dates: *Keep your eyes open wherever you go.* You may find a patch of Japanese knotweed in your own garden or allotment but you may see it anywhere else you may visit.

June -Take leaf samples & return record sheet (Early summer)

August -Take flower samples & return record sheet (Late summer)

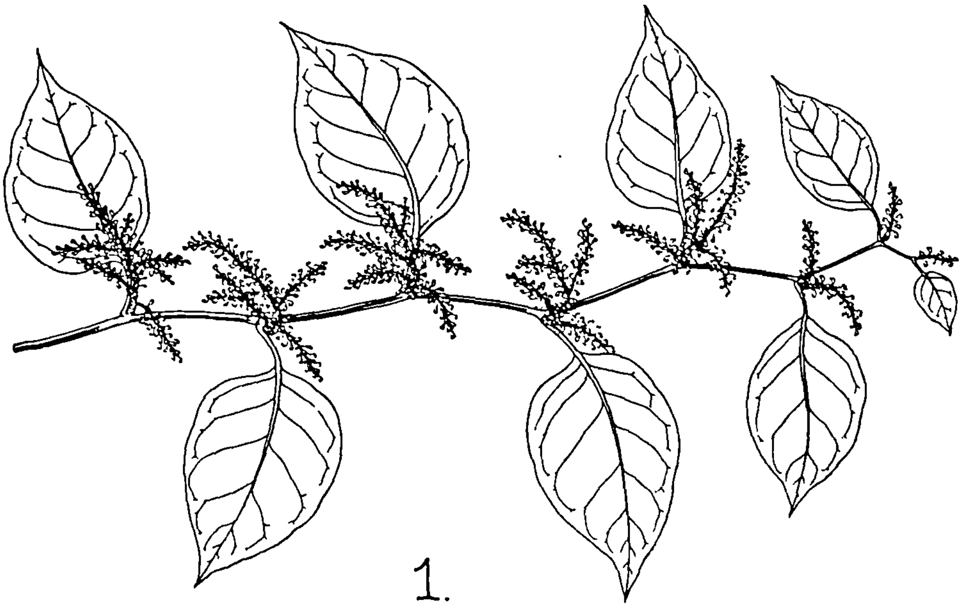
BACKGROUND

Japanese knotweed (*Fallopia japonica* var *japonica* also known as *Polygonum cuspidatum*) was originally introduced to this country in 1850 as an ornamental and fodder plant. Unfortunately it has turned out to be extremely invasive and exceedingly difficult to get rid of once you have got it. It can grow from minute pieces of root and also from pieces of stem. It has now spread through the whole of Britain especially along waterways, on waste ground and along road verges. Once established its dense foliage and aggressive nature excludes other plant species reducing the diversity of native plant species or indeed your favourite garden plants if you are unlucky enough to have it on your land. Japanese knotweed is here to stay but researchers at Loughborough University are looking at ways to try and halt its spread and remove it from sensitive areas. This includes searching for a biological control agent.

Recently a joint research project by Loughborough and Leicester Universities confirmed that an even bigger hybrid of Japanese knotweed *Fallopia x bohemica* is spreading across Britain. It is vital that researchers at Loughborough and Leicester find out more about the distribution and the rate of its spread so that its threat can be assessed and the search for control methods including biological control agents can be started. The locations of any hybrids you find will also be lodged at the Biological Records Centre.

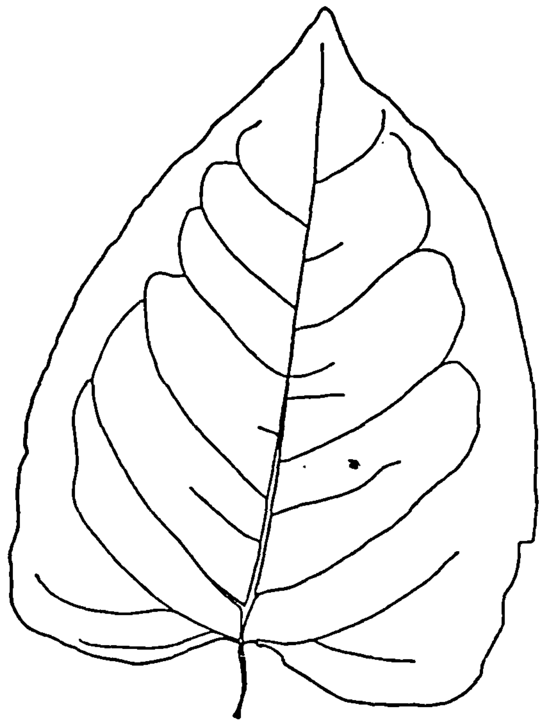
DESCRIPTION

Japanese knotweed grows to about 3 metres (9 feet tall). The stems look like thick bamboo and are usually flecked with purplish-red marks. The leaves are big and broad and the cream-coloured flowers are borne in large decorative clusters. In Britain the foliage dies down during the winter leaving woody stems. The plant then regrows from underground thick creeping stems (rhizomes).



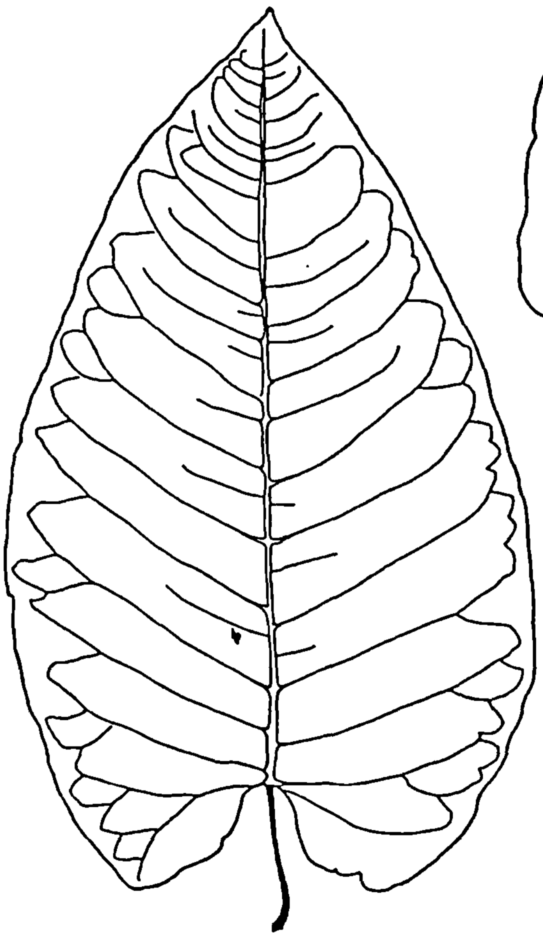
The Japanese Knotweed hybrid we are searching for (*Fallopia x bohemica*) is a cross between *Fallopia sachalinensis* and *Fallopia japonica* var. *japonica*. All these plants look very similar, their main differences are listed below:

	GIANT KNOTWEED *Fallopia sachalinensis*	JAPANESE KNOTWEED *Fallopia japonica* var. *japonica*	HYBRID *Fallopia x bohemica*
Height	Gigantic, up to 4m (approx 13ft)	Large, 2-3m (approx 6.5ft to 8.5ft)	Intermediate, 2.5-4m (approx 8ft to 13ft)
Leaves	Up to 40cm (15.5") long and 22cm (8.5") wide	Up to 15cm (6") long and 10cm (4") wide	Up to 23cm (9") long and 19cm (7.5") wide
	Undersides have scattered, long hairs	Undersides hairless	Undersides of larger leaves have numerous stout hairs easily visible with a hand lens
Main distin-guishing feature	Base of leaf lobbed (See below)	Base of leaf more or less flat	Base of leaf slightly lobed

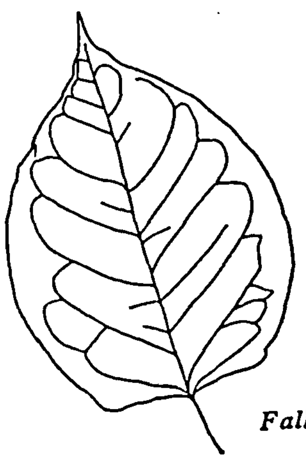


Fallopia x bohemica

5 cm



Fallopia sachalinensis



Fallopia japonica var. japonica

INSTRUCTIONS AND RECORDS (Early Summer)

We do not expect you to be able to distinguish the hybrid from its parents yourselves instead we would like you to send in leaf samples from 'suspect' plants for researchers at Loughborough to identify.

The best time to take samples is in June or July, any later and the leaves become difficult to distinguish.

SAMPLING

The best leaves for identification are at the base of the plant and on the main stem. Miss out the two very oldest leaves, right at the bottom, and **take samples from the third to fifth leaves up.** Gently dry off the leaves with tissue paper, then gently flatten them onto a piece of card and wrap with soft paper. Make a note of the date you take the sample.

NATIONAL GRID REFERENCE

You will need an ordnance survey map of the area where you find your Japanese knotweed/ hybrid. Your library should keep a good range. Find the **six figure** Ordnance Survey grid reference number for the location using the enclosed leaflet 'Using The National Grid'.

Then all you need to do is fill in the form below and send it with your sample to:
LOIS CHILD, I.C.O.L.E., LOUGHBOROUGH UNIVERSITY, LOUGHBOROUGH, LEICESTER, LE11 3TU.

If you find more than one patch of Japanese knotweed/hybrid, please make more copies of the form and make sure you label the leaf samples and forms so we know which ones belong to each other.

JAPANESE KNOTWEED HYBRID SURVEY (HDRA/94/Mem.Exp.4.)
(Early summer)

1. Date you took sample.

2. Which form of knotweed do you think your sample is?

3. Approximate area covered by your patch of knotweed.

4. Describe the habitat of your knotweed/hybrid. e.g. riverside, roadside, garden etc.

5. Approximate location. e.g. ¼ East of Hatton Hospital, off A4177, Nr. Warwick.

6. Vice County

7. Ordnance Survey Grid Reference (must be 6 figures e.g. SK 568 970).

8. Your: Name, address and post code:

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INSTRUCTIONS AND RECORDS (Late Summer)

If you can, return to the site in late summer to sample the flowers. August is normally ideal.

Take a spray of fresh looking flowers, sandwich them between soft paper and card.
As before, please work out the Ordnance Survey six figure grid reference for your patch of japanese knotweed/hybrid.

Again take some leaf samples from the main stem of the plant, third to fifth leaves up from the base. Gently dry them off and wrap with soft paper. (This is to check you are still looking at the same plant as hybrids and parents often grow very close together.)

Please fill in the following record sheet (copy it if necessary) and send it along with your flower samples, preferably in a padded envelope to: LOIS CHILD, I.C.O.L.E., LOUGHBOROUGH UNIVERSITY, LOUGHBOROUGH, LEICS, LE11 3TU.

Thank you for taking part.

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