PREFACE

Weeds and weed control have been continuous features of the association of mankind with the land since the dawn of agriculture. Weeds are integral components of agroecostsyems, are direct competitors with crops, reduce the value of the harvest through contamination, and provide reservoirs of crop pests and pathogens. Around the world cropping systems are managed by farmers to reduce the impact of these most ubiquitous of pests, indeed, the tilling of fields, the defining feature of agriculture, is a major method of weed control. Despite the annual investment of financial resources and labour in weed management, weeds remain a serious constraint to the productivity of farming systems in industrialised and less developed countries alike. Annual worldwide losses to weeds are estimated to be approximately 10-15% of attainable production of the principle food and cash crops, with greater losses being suffered in developing countries than in the industrialised world. For example some 18-20% of cotton, rice and maize production is estimated to be lost to weeds in developing countries of Africa, Asia and the Americas, compared to 9-11% in the industrialised economies of these regions (Terry, 1996). In addition, weed control costs are high with more than $6 billion spent annually on herbicides, tillage and cultivation to control weeds in USA (Chandler, 1991). On smallholdings in less developed countries weeding by hand or with draught animals is a constant burden with much of the drugery being shouldered by women and children. In southern Africa, for example, weed control accounts for up to 60% of the labour used in maize production (Riches *et al.*, 1997).

As a result of a study lasting almost four decades, the authors of the trilogy comprising *The World's Worst Weeds*, from which this Symposium takes it's name, *A Geographical Atlas of World Weeds* and, *World Weeds*, identified 227 species which they suggest are respon-sible for 90% of crop loss attriibutable to weeds in world agriculture (Holm *et al.*, 1977; 1979; 1996). Based on information provided by agronomists, extension workers and farmers in more than 100 countries the authors listed, in order of importance, some 18 species designated as the world's worst weeds.

This symposium brings together contributers with a specialist knowledge of the biology and control of many of the world's most intractable weed genera to review their current status and future prospects for control. Recurrent themes include the reasons why particular species become so dominant, discussed in relation to life history traits, other characteristics of weediness and genetic variability and, the impact of change in cropping systems on shifts in species abundance and persistence. *Cyperus rotundus*, considered by Holm *et al.* (1977) to be the world's worst weed, is discussed in the first paper by John Terry. Although he notes that the Cyperaceae will continue to be important in many situations around the world, a case study shows how African smallholders can improve crop production economically by combining herbicides with other methods of weed control where *C. rotundus* is dominant. Martin Mortimer addresses grass weeds, the group with more species in the "top 18" than any other. Attention is drawn to continuing problems of herbicide resistance evolution, weedy relatives of cereals, the potential for increase in importance of some species with changes in the farming system and, preventative measures based upon an understanding of weed ecology in the context of cropping systems and agronomic practice. Since the publication of *The World's Worst Weeds* the list of the world's worst aquatic weeds has grown from ten to about three dozen. Raghavan

Charudattan adddresses the challenges faced around the world to bring widespread species under control. He demonstrates that successful management of recurrent aquatic problems, for example water hyacinth (*Eichhornia crassipes*), is possible using a combination of biocontrol agents and chemical control, provided adequate financial resources are available. Parasitic weeds in the genera Orobanche and Scrophulariaceae affect the livelihoods of millions of smallholder farmers in sub-Saharran Africa and the Mediterranean basin where they attack staple cereal, pulse and vegetable crops. Malcolm Press, Julie Scholes and Charles Riches discuss the limitations of current control methods and look at current biotechnological approaches to understanding the basis of host crop susceptibility and for designing novel control methods.

The final two papers discuss predictions of the future composition and competitiveness of weed floras in relation to invasion by exotic species and climate change. Invasion is not a recent phenomenon and weed floras in many parts of the world include a sizeable proportion of imigrants, spread as impurities in crop seeds, with fodder, livestock and trade goods. By early in the 20th centuary for example, the weed flora of the Northern Province of South Africa comprised 17% of species of American origin, 40% from Mediterranean and Asiatic areas and 8% from Europe (Burtt-Davy, 1904). Chris Parker reviews systems used to assess the risks from plant introduction but notes that while species known to be agressive can be listed as prohibited under quarantine regulations, it is almost inevitable that there will still be many unpredicted invasions. Several aspects of global climate change are discussed by James Bunce in relation to the competitiveness of weeds and efficacy of weed management practices. He suggests that some weeds may evolve rapidly to take advantage of increases in atmospheric carbon dioxide and points out that current experimental approaches may underestimate the potential impact of global climate change on crop losses due to weeds.

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ABBREVIATIONS

Where abbreviations are necessary the following are permitted without definition

acceptable daily intake	ADI
acetolactate synthase	ALS
acetyl CoA carboxylase	ACCase
acid dissociation constant	pKa
acid equivalent	a.e.
active ingredient	a.i.
approximately	c.
base pair	bp
becquerel	Bq
body weight	b.w.
boiling point	b.p.
British Standards Institution	BSI
by the author last mentioned	*idem.*
centimetre(s)	cm
Chemical Abstracts Services Registry Number	CAS RN
coefficient of varience	CV
colony-forming unit(s)	cfu
compare	cf.
concentration x time product	ct
concentration required to kill 50% of test organisms	LC_{50}
correlation coefficient	*r*
counts per minute	cpm
cultivar	cv.
cultivars	cvs.
dalton	D
day(s)	d
days after treatment	DAT
degrees Celsius (centigrade)	°C
degrees of freedom	df
Department of Environment, Food & Rural Affairs	DEFRA
disintegrations per minute	dpm
dose required to kill 50% of test organisums	LD_{50}
dry matter	d.m.
Edition	Edn
editor	ed.
editors	eds
emulsifiable concentrate	EC
enzyme-linked immuno-sorbant assay	ELISA
fast-protein liquid chromatography	FPLC
Food and Drugs Administration	FDA
for example	e.g.
freezing point	f.p.
gas chromatography-mass spectrometry	gc-ms
gas-liquid chromatography	glc
genetically modified	GM
genetically modified organism	GMO
gram(s)	g
gravity	*g*
growth stage	GS
hectare(s)	ha
high performance (or pressure) liquid chromatography	hplc
high volume	HV
hour	h
infrared	i.r.
inner diameter	id
integrated crop management	ICM
integrated pest management	IPM
International Organization for Standardization	ISO
in the journal last mentioned	*ibid.*
Joules	J
Kelvin	K
kilobase pair	kb
kilodalton	kD
kilogram(s)	kg
kilometres per hour	k/h
least significant difference	LSD
litre(s)	litre(s)
litres per hectare	litres/ha
logarithm, common, base 10	log
logarithm, natural	ln
low volume	LV
mass	*m*
mass per mass	*m/m*
mass per volume	*m/V*
mass spectroscopy	ms
maximum	max.
maximum residue level	MRL
melting point	m.p.
metre(s)	m
metres per second	m/s
milligram(s)	mg
milligrams per litre	mg/litre
milligrams per kg	mg/kg
millilitre(s)	ml
millimetre(s)	mm
minimum	min.
minimum harvest interval	MHI
Ministry of Agriculture Fisheries and Food (England & Wales)	MAFF
minute (time unit)	min
moisture content	M.C.
molar concentration	M
mole	mol
molecular weight (relative)	*Mr*
no observed adverse effect level	NOAEL
no observed effect concentration	NOEC

ABBREVIATIONS

Where abbreviations are necessary the following are permitted without definition

no observed effect level	NOEL
no significant difference	NSD
nuclear magnetic resonance	nmr
number average diameter	n.a.d.
number median diameter	n.m.d.
octanol/water partition coefficient	K_{ow}
organic matter	o.m.
page	p.
pages	pp.
parts per billion	ppb
parts per million	ppm
parts per trillion	ppt
pascal	Pa
percentage	%
polyacrylamide gel electrophoresis	PAGE
polymerase chain reaction	PCR
post-emergence	post-em.
power take off	p.t.o.
pre-emergence	pre-em.
pre-plant incorporated	ppi
probability (statistical)	*P*
relative humidity	r.h.
revolutions per minute	rev/min
second (time unit)	s
standard error	SE
standard error difference	SED
standard error of means	SEM
soluble powder	SP
species (singular)	sp.
species (plural)	spp.
square metre	m^2
subspecies	ssp.
surface mean diameter	s.m.d.
suspension concentrate	SC
systemic acquired resistance	SAR
tandem mass spectrometry	MS-MS
technical grade	tech.
temperature	temp.
that is	*i.e.*
thin-layer chromatography	tlc
time for 50% loss; half life	DT_{50}
tonne(s)	t
ultra low volume	ULV
ultraviolet	u.v.
United Kingdom	UK
United States	US
United States Department of Agriculture	USDA
vapour pressure	v.p.
variety (wild plant use)	var.
volume	*V*
volume median diameter	v.m.d.
water dispersible granule	WG
weight	*wt*
weight by volume	*wt/v*
(mass by volume is more correct)	(m/V)
weight by weight	*wt/wt*
(mass by mass is more correct)	*(m/m)*
wettable powder	WP

less than		$<$
more than		$>$
not less than		$\nless$
not more than		$\ngtr$
Multiplying symbols-		Prefixes
mega	($\times 10^{6}$)	M
kilo	($\times 10^{3}$)	k
milli	($\times 10^{-3}$)	m
micro	($\times 10^{-6}$)	μ
nano	($\times 10^{-9}$)	n
pico	($\times 10^{-12}$)	p

THE *CYPERACEAE* – STILL THE WORLD'S WORST WEEDS?

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The Cyperaceae - still the world's worst weeds?

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ABSTRACT

The Cyperaceae family is a well-represented in world agriculture by over 230 weeds, of which the most important are within the genus *Cyperus*. Four of the most problematical species are the perennial sedges *C. rotundus* and *C. esculentus*, and the annual sedges *C. difformis* and *C. iria*. The reasons for their importance are discussed in relation to characteristics of weediness, including reproduction, growth, plasticity, competitiveness and resistance to control. Mechanical, cultural, biological and chemical methods of control are considered and an example of the management of *C. rotundus* on smallholder farming systems in Ghana is presented as a case history. The future importance of sedge weeds is discussed in terms of climate change, intensification of agriculture and herbicide resistance in crops and weeds.

INTRODUCTION

After collating the information from thousands of sources in over 120 countries, Holm *et al.* (1977) derived a list of the18 most serious weeds, ranked in approximate order of importance. The first sentence describing number one on the list is, "*Cyperus rotundus* is the world's worst weed", a sentiment that, ever since, has been expressed in innumerable books, scientific papers and conferences, and quoted in such a popular tome as *The Guinness Book of Records*. The reputation of *C. rotundus* is earned by its reported occurrence as a weed of 52 crops in 92 countries. Holm *et al.* (1977) described an additional 58 weeds that they considered to be amongst the worst, including the annual sedges *C. difformis* L. (in 46 countries), *C. iria* L. (in 22 countries), *Fimbristylis miliacea* (L.) Vahl (in 21 countries) and *F. dichotoma* (L.) Vahl (in 21 countries). In their book, *A Geographical Atlas of World Weeds*, Holm *et al.* (1979) list 227 species in the family Cyperaceae (i.e. sedges) and, in the third book of their trilogy, Holm *et al.* (1997) describe and illustrate seven sedge weeds. It is evident that the Cyperaceae are very well represented in the world's weeds but are they still amongst the most important over 25 years after Holm and his colleagues completed their surveys?

THE CYPERACEAE FAMILY

The Cyperaceae is a cosmopolitan family of monocotyledonous plants with about 5,000 species according to Bruhl (1995), though other authors quote about 4,000 species in 90 genera (Haines & Lye, 1983) or 3,600 species in 115 genera (Mabberley, 1987). The discrepancy between authors is an indication of the difficulty experienced by taxonomists in classifying the Cypereaceae. The main problem when basing classification on traditional methods is that the flowers are small and it is very difficult to interpret the morphology of the inflorescence (Metcalfe, 1971). Bruhl (1995) summarises eight systems of classifying the Cyperaceae genera and, based on cladistic (i.e. evolutionary) and phenetic (i.e. observable traits) analyses, proposes the division of the Cyperaceae into two subfamilies and 12 tribes (Table 1). Eight tribes contain weedy species, especially the Cypereae and Scirpeae, which each contain five genera. However, some authors do not recognise the names of all genera: for example, Haines & Lye (1983) place *Kyllinga*, *Mariscus* and *Pycreus* within the genus *Cyperus*, and *Bolboschoenus* within the genus *Schoenoplectus*. The synonomy of some weeds is indicative of the confusing taxonomy. *Bolboschoenus maritimus* (L.) Palla, for example, is also known by the synonyms *Scirpus maritimus* L. and *Schoenoplectus maritimus* (L.) Lye.

Table 1. Suprageneric classification of the Cyperaceae (Bruhl, 1995) and significant weed genera (number of genera and species in each tribe are given in parenthesis)

Subfamily	Tribe (genera/species)	Genera with weeds
Cyperoidea	Cypereae (17/878)	*Cyperus, Kyllinga, Lipocarpha, Mariscus, Pycreus*
	Scirpeae (28/518)	*Bolboschoenus, Eleocharis, Fuirena, Schoenoplectus, Scirpus*
	Abildgaardieae (7/430)	*Bulbostylis, Fimbristylis*
	Arthrostylideae (4/6)	-
Caricoideae	Rhynchosporeae (4/273)	*Rhynchospora*
	Schoeneae (27/379)	*Cladium*
	Cryptangieae (5/92)	-
	Trilepideae (4/15)	-
	Cariceae (6/2089)	*Carex*
	Sclerieae (2/201)	*Scleria*
	Bisboeckelereae (4/22)	-
	Hypolytreae (14/159)	*Lepironia, Mapania, Thoracostachyum*

The weedy species and genera of Cyperaceae can be ascertained by perusing national and international literature. Much of the world is covered in *A Geographical Atlas of World Weeds* (Holm *et al.*, 1979) but other publications can be found for China (Zhirong, 1990), south and south-east Asia (Moody, 1989), East Africa (Terry, 1976), West Africa (Akobundu & Agyakwa, 1987; Johnson, 1997; Le Bourgeois & Merlier, 1995), Australia (Parsons & Cuthbertson, 1992), Brazil (Lorenzi, 1982) and Indonesia (Soerjani *et al.*, 1987). The CAB abstracts database (CAB, 1973-2001), is also a valuable source of information. If one assumes that the interest in a genus is directly related to the times it is cited in the literature, the *Cyperus* genus (including *Kyllinga*, *Mariscus* and *Pycreus*) far exceeds that of the other genera (Fig.1). This is consistent for the three primary sources, Holm *et al.* (1979), other publications (see above) and the CABI abstracts service. *Carex* (including *Schoenoplectus*), *Eleocharis*, *Fimbristylis* (including *Bulbostylis*) and *Scirpus* each receive about 10% of the total number of citations for the Cyperaceae family but this is far exceeded by about 45% of citations for *Cyperus*.

Some examples of weeds in the family Cyperaceae and their associated crops are given in Table 2. The close link between these weeds and rice is characteristic of a family that is associated with damp, wet or marshy regions of the world (Heywood, 1978).

RELATIVE IMPORTANCE OF CYPERACEAE WEEDS

The survey published by Holm *et al.* (1977) ranked weeds according to their importance as perceived by the researchers and their numerous contacts around the world. This led to the

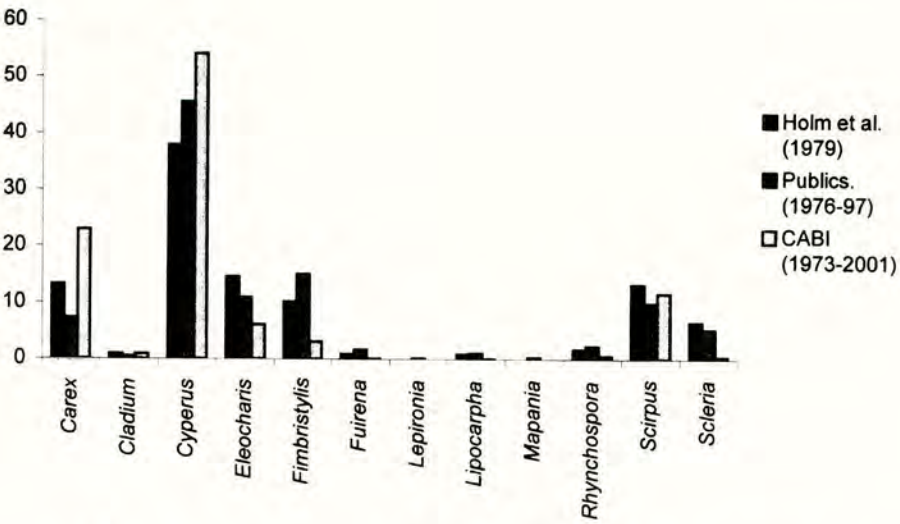

Fig. 1. Frequency of citation of Cyperaceae genera from three sources

Table 2. Examples of weeds from 12 genera of Cyperaceae and their associated crops

Species	Crops	Reference
Carex rigescens (Franch.) V. Krecz.	Orchards	Zhirong, 1990
Cladium mariscus (L.) Pohl	Rice	Moody, 1989
Cyperus rotundus L.	Numerous	Holm *et al.*, 1977
Eleocharis acicularis (L.) Roem & Schult.	Rice	Soerjani *et al.*, 1987
Fimbristylis miliacea (L.) Vahl	Rice, sugar cane	Soerjani *et al.*, 1987
Fuirena ciliaris (L.) Roxb.	Rice	Soerjani *et al.*, 1987
Lepironia articulata (Retz.) Domin	Rice	Moody, 1989
Lipocarpha chinensis (Osbeck) Kern	Rice	Soerjani *et al.*, 1987
Mapania cuspidata (Miq.) Uittien	Rice	Moody, 1989
Rhynchospora corymbosa (L.) Britton	Rice	Johnson, 1997
Scirpus maritimus L.	Rice	Johnson, 1997
Scleria depressa (C.B. Clarke) Nelmes	Rice	Johnson, 1997

conclusions that *C. rotundus* was the worst weed and *C esculentus* ranked 16th, whilst *C. difformis* and *C. iria* were in the second league of important weeds within the ranking of 19th to 76th. Using the number of citations in the CAB abstracts database (CAB, 1973-2001) as a criterion for ranking importance, the top 18 weeds given by Holm *et al.* come out in a different order (Fig. 2). *Cyperus rotundus* appears as 6th after *Cynodon dactylon* (1st), *Chenopodium album* (2nd), *Echinochloa crus-galli* (3rd), *Avena fatua* (4th) and *Sorghum halepense* (5th). *Cyperus esculentus* moves up to 13th position whilst *C. difformis* and *C. iria* remain in the lower ranks. There is no disputing the importance of *C. dactylon* but its high ranking is partly due to the large number of abstracts where it is cited as a crop, Bermuda grass, not as a weed.

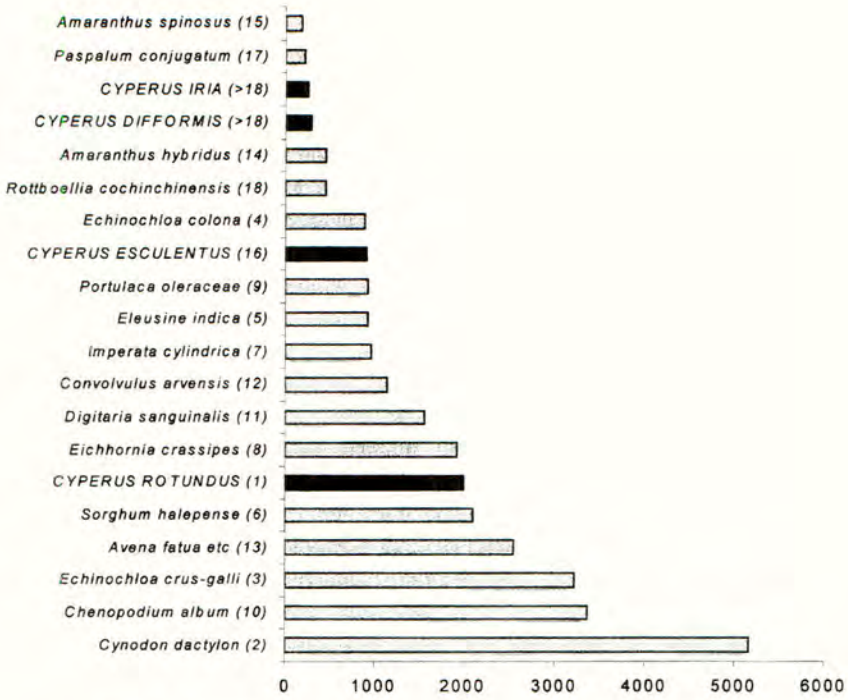

Fig. 2. Frequency of citation of weeds in CAB (1973 - 2001)
(importance rankings by Holm *et al.* (1977) are given in parenthesis)

It is somewhat academic and unimportant to compare systems of ranking weeds. When they are within the top 100 species, all are important, whether their distributions are local, regional or global. However, four sedge weeds are consistently considered to be among the worst weeds in the world, *C. difformis*, *C. esculentus*, *C. iria* and *C. rotundus*. The question is, whether they are more or less important today than when Holm *et al.* (1977) published their survey? Using the CAB abstract database (CAB, 1973-2001) as an indicator of importance, it appears that *C. rotundus* received more attention in the 1970s than in subsequent decades (Fig. 3). The number of citations on *C. esculentus* peaked in the late 1970s but has declined steadily thereafter. There appears to have been a steady increase in the number of citations on *C. iria* throughout the 30-year period. The pattern is little changed when the citations of these sedge weeds are calculated as a percentage of citations for all abstracts containing the key word 'weed' during the same five-year periods. It is perhaps no coincidence that glyphosate herbicide became available for commercial use during the mid 1970s, leading to a spate of research on many perennial weeds, including *C. rotundus* and *C. esculentus*. Perhaps the exposure by Holm *et al.* of the importance of *C. rotundus* and *C. esculentus* in 1977 promoted a surge of research interest in these weeds.

WHY THE SEDGE WEEDS ARE IMPORTANT

The four sedge weeds that are considered to be most important have many characteristic traits of weediness (Table 3), some of which are discussed below.

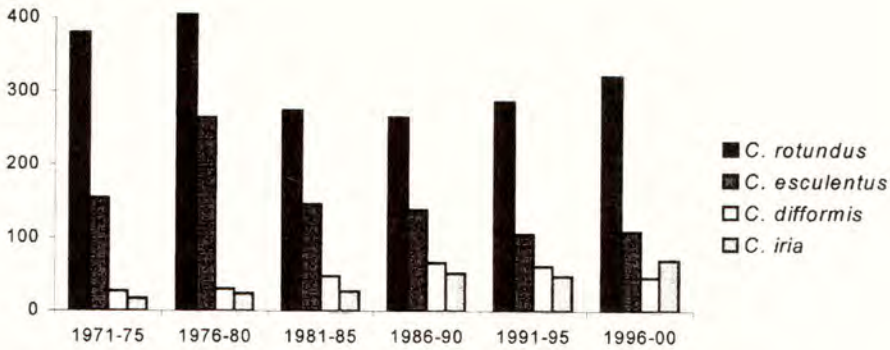

Fig. 3. No. of citations of *Cyperus* spp. per five-year period in *Weed Abstracts* (CAB, 1971-1972) and CAB abstracts service (CAB, 1973-2001)

Table 3. Weediness characteristics (based on Baker, 1965 and Zimdahl, 1999) found in four important sedge weeds

Characteristics	*Cyperus rotundus*	*Cyperus esculentus*	*Cyperus difformis*	*Cyperus iria*
Rapid growth from seeds or propagules	++	++	++	++
Quick maturation of the plant	+	++	++	+
Dual modes of reproduction	+	++	O	O
Environmental plasticity	++	++	++	++
Often self compatible		O		
Cross-pollinated by non-specialised flower visitors or by wind		+		
Resist detrimental environmental factors	++	++	+	+
Weed seeds exhibit several kinds of dormancy	na			+
Weed seeds same size and shape as crop seed	O	O	O	O
Annuals produce more than one generation per year	na	na	++	++
Large number of viable seeds per plant	O	+	++	++
Long- and short-range seed dispersal mechanisms	-	-	-	-
Deep penetration of roots in the soil	++	+	-	-
Rapid growth of roots and/or rhizomes	++	++	+	+
Severed vegetative organs rapidly regenerate new plants	++	++	na	na
Perennating organs have large food reserves to withstand environmental stress and intensive cultivation	++	++	na	na
Repel grazing animals (e.g. by taste, odour or spines)	+	-	-	-
Competitive for light, nutrients and water	++	++	++	++
Allelopathic	+	+		
Resist control, including herbicides	++	+	+	+

Key: + = good, ++ = very good, - = nothing special, O = poor, na = not applicable

Efficient reproduction

Cyperus rotundus produces seeds that have little or no viability but it is very proficient at producing tubers, the main form of propagation of this weed. Horowitz (1972) has reported that 2-3 million tubers/ha/week can be produced during active growing periods, yielding 30-40 million tubers/ha that can weigh 40 tonnes. Tuber populations have a half-life of 16 months and a predicted longevity (99% mortality) of 42 months (Neeser *et al.*, 1997).

Tuber weights of 18 t/ha and populations of 30 million/ha have been recorded for *C. esculentus* (Holm *et al.*, 1977) but this weed can also reproduce significantly by seed; there are records of single plants producing 1,500 seed with viability from 50 to 95% (Justice & Whitehead, 1946).

Cyperus difformis and *C. iria* are both annual weeds, sometimes behaving as perennials, and reproduce by seeds. In the USA, Hill *et al.* (1963) demonstrated that one seedling of *C. esculentus* could develop a plant system in one season capable of producing 90,000 seeds with better than 50% viability. In Italy, Jacometi (1912) reported that one plant of *C. difformis* could produce 50,000 seeds with about 60% germination. Such fecundity enables *C. difformis* seedlings to become established at high densities, allowing this weed to rapidly cover the ground and become the dominant vegetation. In tropical climates, the plant can flower and produce seeds throughout the year, providing that sufficient moisture is present.

Holm *et al.* (1977) report that a single plant of *C. iria* can produce 5,000 seeds, 40% of which can germinate immediately and most others after a period of dormancy.

Rapid growth and maturation

Tubers of *C. rotundus* can sprout in 7-10 days and produce new basal bulbs and shoots within 3-4 weeks. Flowering can occur within 3-8 weeks of shoot emergence and, although insignificant for viable seed production, indicates that the plant is mature and competing for resources required by crop plants.

Temperatures, day length and soil moisture are all influential in the growth of development of the shoots, tubers and flowers of *C. esculentus*. Under good conditions, the life cycle from germination to production of tubers and seeds is completed within three months.

Cyperus difformis can complete its vegetative and reproductive life cycle in 30 days (Ampong-Nyarko & De Datta, 1991; Vaillant, 1967), making it possible for several generations to be completed in one year.

Surprisingly little has been published on the life cycle of *C. iria* under natural conditions but it is clearly capable of rapid growth and establishment in order to achieve its status as an important weed of rice.

Environmental plasticity

Cyperus rotundus is widespread in the tropics and subtropics, growing in almost every soil type, elevation, humidity, soil moisture and pH, but not in soils with a high salt content (Holm *et al.*, 1977). Its range at increasing latitudes and altitudes is limited by cold temperatures. It occurs in cultivated fields, fallow land, neglected areas, road and rail sides, banks of irrigation canals and streams, edges of woods and sand dunes. Generally, it does not tolerate shade. *C. esculentus* also grows under a wide range of conditions, including most soil types, but it tolerates higher soil moisture than *C. rotundus* and survives in cooler climates. Tolerance of such a wide range of conditions enables *C. rotundus* and *C. esculentus* to infest a wide range of crops. C. *difformis* is usually found on flooded or very wet soils, open soggy grasslands, pools (but not in deep water) and riverbanks where it often becomes the dominant plant. It prefers fertile soils but can also grow on poor sandy or clay soils (Soerjani *et al.*, 1987). It is one of the commonest weeds of paddy or flooded rice but it has also been reported as a weed of upland rice and crops such as bananas, sugar cane, tea and maize (Holm *et al.*, 1977). *C. iria* is also found in moist to wet soils, including river banks and ditches where it is an important weed of lowland and irrigated rice fields but less so in the upland crop.

Competitive for light, nutrients and water

All four sedge weeds are noted for being competitive in crops. Examples of the effects of *C. rotundus* on crop yields include 35-89% reduction in vegetables (Williams & Warren, 1975), 30% loss in cotton (Cruz *et al.*, 1969), 100% loss in radish (Santos *et al.*, 1998) and 75% loss in sugar cane harvest (Cerrizuela, 1965). Even the growth of tree crops can be reduced; for example, mulberries in Japan, citrus in Israel and coffee in Kenya (Holm *et al.*, 1977). Much of this can be attributed to the capacity of *C. rotundus* to remove nutrients from the soil and store them in its tubers, making them unavailable to crops (Bhardwaj & Verma, 1968; Rochecouste, 1956).

Yield losses of 26-79% have been recorded when maize is infested with *C. esculentus* with an 8% yield reduction for every increase of 100 shoots/m (Stoller *et al.*, 1979). Patterson *et al.* (1980) observed 52-61% reductions in yields of seed cotton when densities of *C. esculentus* were 90 shoots/m. Uncontrolled *C. esculentus* in soybean caused yield losses of 60-87% (Simkins & Doll, 1980).

It is difficult to separate the competitive effects of sedge weeds from those of other components of the weed flora but 12-50% reductions in rice grain yields have been caused by *C. difformis* and 40% reductions by *C. iria* (Ampong-Nyarko & De Datta, 1991). *C. difformis* is not a particularly tall weed but it can have a high biomass per hectare. The rate of appearance of *C. difformis* and its tiller numbers are the main factors causing yield loss in rice (Yu, 1992).

Resistance to control

Much of the reputation of *C. rotundus* and *C. esculentus* is based on their propensity to survive, or even multiply, when subjected to methods of control that would destroy less robust weeds. Physical, cultural, biological and chemical methods have been used with various levels of success.

Physical control of perennial sedge weeds

Tillage, the most traditional of weeding practices, has little effect on *C. rotundus* unless an absurdly high and expensive number of operations are deployed. In India, Sinha & Thakur (1967) showed that cultivations every 1, 2 or 3 weeks over a period of two years reduced tuber populations by about 99%. However, cultivations every 5 or 6 weeks gave an increase in tubers of 37% and 67%, respectively. Similar results were obtained in the USA where tillage every 3 weeks reduced tuber populations by 80% but tubers increased when the interval between tilling was 4 weeks, regardless of soil type, but tubers were more difficult to kill on heavy wet clay (Smith & Mayton, 1938; 1942). For tillage to be effective, it must be done with sufficient frequency to exhaust food reserves in the tubers as they continue to produce new shoots. However, the capacity for regeneration is so high that this is largely impractical on the grounds of cost, disturbance to crops and damage to soil structure. Tubers can be destroyed by desiccation if tillage can sever tubers from roots and expose them to heat and sunlight at the soil surface but this, too, can be impractical without sacrificing most or all of a cropping season.

Cyperus esculentus is not easily controlled by cultivation (Doll, 1983). Under experimental conditions, it has been shown that 14 weekly hoeings in cotton could reduce the tuber population to 24% of the original density. Cultivation helps to suppress *C. esculentus* if done repeatedly when shoots reach the 5 to 7 leaf stage. Shallow cultivation will aid in the destruction of emerged shoots but new shoots growing from dormant buds on the tubers quickly replace them. Two to four cultivations at the beginning of the growing season should give enough time for the crop to become established. Tubers of *C. esculentus* are not as susceptible to desiccation as those of purple nutsedge.

Alternative methods for the physical control of perennial sedge weeds usually have limited practical utility. Thick layers of organic mulch give only temporary suppression of growth but 1000-gauge black polyethylene is effective in pineapples and tree crop nurseries until it deteriorates. Mowing or cutting is feasible for a few crops but, although the result may be aesthetically pleasing in a tree crop, control of shoots and tubers is minimal and the cut plants continue to take water and nutrients from the soil.

Cultural control of perennial sedge weeds

Cyperus rotundus and *C. esculentus* are both poor competitors beneath the shady canopies of vigorous, well established crops. Therefore, any practice which hastens the formation of a crop canopy should be used (Doll, 1983). This includes selecting fast growing crops, using the narrowest row spacing practical, planting relatively high crop densities and keeping the crops healthy. If standing water can be maintained in transplanted rice, *C. rotundus* will not be a serious weed. Crop rotation can be an effective practice. Fallowing for four years has given more than 99% reduction in the number of *C. esculentus* tubers on a peat soil (Tumbleson & Kommedahl, 1961) and a 90% reduction after two years on an upland soil (Bell *et al.*, 1962) but this may not be option where a continuous cropping cycle is required.

Biological control of sedge weeds

Effective biological control of the *C. esculentus* and *C. rotundus* has been a goal of weed scientists for many decades. Phatak *et al.* (1987) list 132 insects that have been associated with these weeds, together with 26 fungal pathogens, ten nematodes, two bacteria, one virus and three vertebrates (pigs, ducks and geese). Four insects on perennial sedge weeds have been studied in detail: three moths, *Bactra verutana* Zeller in the USA, *B. minima* Meyrick and *B. venosana* Zeller in the Indian subcontinent and one weevil, *Athesapeuta cyperi* Marshall in south east Asia. All are adequately host-specific but none has proved effective as a classical biological control agent. Studies on the inundative biological control of *C. rotundus* with *B. verutana* has shown that aboveground growth of the weed can be reduced by 30 to 40% within 4-7 weeks of last release (Frick & Chandler 1978). Yield of seed cotton following release of *B. verutana* to control *C. rotundus* was equivalent to yields from crops not infested with the weed. However, a cost-effective procedure has not been developed for field scale use.

Puccinia canaliculata (Schw.) Lagerh., a rust fungus, has been registered as the bioherbicide Dr BioSedge® for the control of *C. esculentus* (Rosskopf *et al.*, 1999). Applied at the rate of 5 mg of uredospores/ha, this rust pathogen spreads quickly and can cause a 90% reduction in fresh weight of the weed. It can also cause 46% reduction in shoot density and 66% inhibition of new tuber formation. However, production of an inoculum is a problem because *P. canaliculata* is an obligate parasite and it has not yet been developed for commercial use. Another fungus, *Dactylaria higginsii* (Luttrell) M.B. Ellis, has been patented for the control of several *Cyperus* spp., including *C. rotundus* and *C. esculentus* (Kadir & Charudattan, 1996). This fungus kills aboveground shoots and limits tuber production, reducing the competitiveness of the weeds in crops.

There is some optimism that methods will be found for the biological control *of C. rotundus* and *C. esculentus* but there is a need to find more organisms and to develop methods for mass rearing or culturing, formulation, storage and application.

Chemical control of sedge weeds

The introduction of herbicides is a factor associated with the increasing importance of the perennial sedge weeds. Many products remove the readily controlled annual weeds, allowing the perennial sedges to establish in the absence of competition. It is not unusual to replace a mixed weed flora by one that one that is totally dominated by *C. rotundus* after using, for example, simazine in maize or paraquat in coffee.

Control of the annual sedges *C. difformis* and *C. iria* in rice is feasible with several herbicides that are widely used for many of the commonly occurring weeds of this crop. The perennial sedges, however, are less amenable to control; whilst a large number of products is available for a range of crops (Table 4), most provide only temporary suppression of growth, without killing the tubers, but allowing time for establishment of the crop. Glyphosate is one of the few products available that will kill the foliage, rhizomes and tubers of *C. rotundus* and *C. esculentus*. It is best applied to these actively growing sedges with a large leaf area through which the herbicide is absorbed. Rapid translocation occurs throughout the plant to tubers that are the sink for metabolites and remain attached to the aboveground shoots by a network of rhizomes. This makes *C. rotundus* rather more susceptible to glyphosate than *C. esculentus* because the tubers are linked in chains along persistent rhizomes that continually produce new terminal tubers. By contrast, *C. esculentus* produces single tubers at the ends of rhizomes that cease to be metabolic sinks after they are fully grown. Furthermore, rhizomes connecting the tubers of *C. esculentus* to the shoots persist for a relatively short time, leaving isolated tubers in the soil that cannot be reached by a translocated herbicide. The timing of glyphosate application is important in determining the level of control of *C. esculentus*. Better control is usually obtained by applications early in the season: *C. esculentus* is more susceptible to glyphosate at the 4-6 leaf stage than at 6-8 leaves (Stoller *et al.*, 1975) and greater tuber reductions are achieved by glyphosate applications at the 9-11 leaf stage (21 days after emergence) than at pre-flowering, 66 days after emergence (Kogan & Gonzalez, 1979).

Table 4. Herbicides associated with the control or suppression of *Cyperus* spp. in crops*

Herbicide	*Cyperus rotundus*	*Cyperus esculentus*	*Cyperus difformis*	*Cyperus iria*
acetochlor		mai		
alachlor		bea, gro, mai, sor, soy		
bensulfuron-ethyl			rice	rice
bentazon	rice	bea, gro, mai, rice, sor, soy mai	rice	rice
bifenox			rice	rice
bromacil	cit, pin, sis	cit, pin, sis		
butachlor			rice	rice
butylate	mai	mai		
chlorimuron-ethyl		soy		
cinmethylin		rice	rice	rice
cycloate	spi, sugb	spi, sugb		
2,4-D		rice, sugc	rice	rice
dicamba			rice	
dimethenamid		bea, gro, mai, sor, soy		gro, mai, sor, soy
EPTC	mai	mai		
ethofumesate	sugb	sugb		
fomesafen		soy		
glufosinate-ammonium		soy		
glyphosate	tree	tree		
halosulfuron-methyl	mai	mai, sor		
imazamox		soy		
imazapyc	gro			
imazaquin		soy		
imazethapyr	gro	gro, mai, soy		
MCPA			rice	rice
metolachlor		bea, cot, gro, mai, mun, peas, pot, saf, sor, soy, sugc, sun		
molinate	cot	rice	rice	rice
MSMA	cas, cot	cas, cot		
norflurazon		cot, soy		
oxadiazon			rice	rice
oxasulfuron		soy		
pebulate	sugb, tob, tom	sugb, tob, tom		
piperophos			rice	rice
primisulfuron-methyl		mai		
propachlor		flax		
propanil			rice	rice
pyrithiobac sodium		cot		
rimsulfuron		mai, pot		
sulfentrazone		soy		
terbacil		apple, nuts		
thiobencarb			rice	rice
vernolate	gro	gro, soy		

*Crop key: bea = beans (*Phaseolus*), cas = cassava, cit = citrus, cot = cotton, gro = groundnut, mai = maize (including sweet corn), mun = mung bean, pin = pineapple, pot = potato (Irish), saf = safflower, sis = sisal, sor = sorghum, soy = soyabean, spi = spinach, sugb = sugar beet, sugc = sugar cane, sun = sunflower, tob = tobacco, tom = tomato, tree = tree crops (citrus, coffee, cocoa, rubber, tea, etc.)

The acquisition of resistance to herbicides by weeds is a problem for the control of many species but, so far, the only example for sedge weeds is the resistance to bensulfuron-methyl in *C. difformis* in Australia and the USA (WeedScience.com, 2001). The mode of action of this herbicide is by inhibition of acetolactate synthase (ALS) so there is a possibility of cross-resistance to other Group B/2 herbicides that have this action, including sulfonylureas and imidazolinones.

The advent of herbicide resistant crops will have an impact on how sedge weeds can be controlled. Glyphosate, one of the most effective herbicides for the control of *C. rotundus* and *C. esculentus*, could not be used as a selective herbicide in annual field crops, though management strategies exist for using this herbicide within a cropping system (see case history below). However, glyphosate-resistant soybean, oilseed rape, cotton and maize have become available in North America (Duke, 1999) and elsewhere, making it possible for the selective control of sedge weeds and other problem species by glyphosate in these crops. Resistance in crops to other herbicides active against sedge weeds is also available for glufosinate and imidazolinones in oilseed rape and maize, and sulfonylureas in soyabean (Duke, 1999).

Case history of the control of *C. rotundus*

There are many examples of where glyphosate has been used for the control of sedge weeds. The following case history demonstrates how *C. rotundus* can be controlled effectively and economically within smallholder farming systems in a developing country.

Vertisols and vertic clays represent a vast crop production resource (300 million hectares world-wide) that is underutilised, mainly because of problems with soil physical characteristics (particularly relating to water) and weeds. These montmorillonitic clays are generally more fertile and have higher water holding capacities than many tropical soils, but they are difficult to manage as they are very sticky when wet and hard and cloddy when dry. Research in Ghana has shown that it is technically possible to increase crop yields by 90% in normal wet seasons by using raised (camber) beds to control water, but further increases in yield are prevented by high populations of *C. rotundus*. These challenges were addressed by research on farms and on a research station to determine the effectiveness of glyphosate and camber beds for weed and water management and crop production in maize-based farming systems (Darkwa *et al.*, 2001).

Field trials started on a research station in March 1997 on a site with high densities of tubers and continued for six seasons over a period of three years. Camber beds were made by tractor tillage to create a raised profile 4.8 m wide and 40 cm high (later settling to 30 cm high) from the trough to the top of the bed. Tractors were also used to make flat plots in the same way as used by farmers. In subsequent seasons, the flat plots were prepared by disc ploughing and harrowing whilst the camber beds were lightly cultivated with a polydisc. Maize was grown in the major rainy seasons whilst cowpeas were grown in the minor seasons, both using varieties and agronomic practices used by local farmers. On half of the flat and camber bed plots, glyphosate was applied at 1.8 kg a.e./ha to weeds that had been allowed to grow at the beginning of the wet season. Supplementary hand weeding was done, usually once, to remove late germinating weeds that were not controlled by glyphosate. On the other plots, weeds were removed by hand weeding when necessary, usually twice during the season.

Tuber densities of *C. rotundus* were evaluated in July 1998, November 1998 and November 1999 (i.e. towards the end of the third, fourth and sixth seasons) by extracting soil from quadrats to a depth of 30 cm (Table 5). These showed that repeated use of glyphosate significantly reduced tuber densities. By the third season of the trial, tuber numbers had been reduced by 72%, in the fourth season by 95% and, in the sixth season by more than 99%. Other researchers have found similar results (Zandstra *et al.*, 1974; Charles, 1995).

Table 5. Effect of glyphosate and hand weeding on tuber densities of *C. rotundus* on a Vertisol in Ghana in three seasons. Densities (tubers/m) are expressed as back-transformed means after statistical analysis.

Date (season)	Flat		CB		F-test	
	Hand-weed	Glyph-osate	Hand-weed	Glyph-osate	CB>F (F>CB)	Hand>Gly
July '98 (3rd)	503	119	765	205	*	***
Nov '98 (4th)	602	18	826	40	*	**
Nov '99 (6th)	842	4	811	2	(NS)	***

*, **, *** = Means differ significantly at probabilities of 0.05, 0.01 and 0.001. NS = not significant

Yields of maize on glyphosate-treated plots were always significantly greater than on hand-weeded plots (Table 6). This is undoubtedly due to the suppression of all weed growth early in the season when the crop was most vulnerable to competition. It is not possible to say what proportion of the increase is due to control of *C. rotundus* but the result is consistent with the findings of other researchers who have observed yield increases after control of this weed (Williams & Warren, 1975).

Table 6. Mean yields of maize grain (kg/ha) on flat plots and camber beds after treatments with hand weeding and glyphosate

Year	Flat		Camber Bed		F-test	
	Hand-weed	Glyph-osate	Hand-weed	Glyph-osate	F>CB (CB>F)	Gly>Hand
1997	1234	2315	1399	2731	(NS)	***
1998	828	2463	504	1541	***	***
1999	665	2925	1554	3576	(**)	***

*, **, *** = Means differ significantly at probabilities of 0.05, 0.01 and 0.001, respectively.
NS = not significant

Using a cost-benefit model developed from data collected on Vertisols in Ghana, the economics of using glyphosate were compared for farmers with three levels of inputs. Low input farmers use family labour and purchase no inputs; medium input farmers buy seed, use half rates of fertiliser and hire some labour; high input farmers are semi-commercial growers, use full rates of fertiliser and hire all labour. In all cases, glyphosate compared very favourably to hand-weeding in maize. Gross margins for glyphosate treatments were higher than for hand-weeding because of the reduced labour costs for weed control and greater yields. For glyphosate treatments on camber beds, the gross margins can be as high as £254/ha, compared with £57/ha for low-input farmers using hand-weeding on flat plots.

FUTURE IMPORTANCE OF SEDGE WEEDS

There can be no doubt that sedge weeds will remain as a significant component of the weed floras of crops around the world. Global warming will extend the range of these mainly tropical and sub-tropical species into more temperate areas. *Cyperus esculentus*, for example, recorded as a weed in France, Portugal and Switzerland by Holm *et al.* (1977) has the potential to invade more northerly parts of Europe to become a problem in the flower and horticultural industries of south west England and the Channel Islands.

Cyperus rotundus and *C. esculentus* are both associated with intensification of agriculture. Practices that promote continuous cropping, reduce fallowing, increase irrigation and deploy herbicides are becoming more widely adopted, especially in the developing countries of the world. Sedge weeds, often a minor component of a diverse weed flora on peasant farms, assume a greater significance as the farmers take up new technologies and crop management strategies. The annual sedge weeds, *C. iria* and *C. difformis* are problematical in paddy rice and likely to remain so as world production increases. The area of paddy rice harvested in the world has increased from 142 million ha in 1975 to 154 million ha in 2000, of which about 97% is grown in developing countries (FAO, 2001).

Chemical control of sedge weeds is likely to increase as the developing countries become greater users of herbicides. There does not appear to be any immediate threat of resistance developing in *C. rotundus* and *C. esculentus* because they reproduce primarily by vegetative means. However, the annual sedge, *C. difformis* has acquired resistance to bensulfuron-methyl and there must be a risk that it will have, or acquire, resistance to other sulfonylurea herbicides used in rice. There is not, at present, any record of herbicide resistance in *C. iria* but this must remain a possibility for the future.

Herbicide resistant crops will increase scope for the control of perennial sedge weeds, especially for the use of glyphosate. Doll (2000) notes the potential for controlling *C. rotundus* with glyphosate in transgenic maize and soyabean but cautions that the lower susceptibility of *C. esculentus* to glyphosate could quickly lead to an increase in this weed in rotations of transgenic maize and soyabean. Herbicide resistance technology could transform a serious weed problem into a manageable situation if it becomes widely adopted and is affordable in the developing world.

Despite recent promising discoveries of biological control agents, there seems to be little prospect of them reducing the importance and impact of sedge weeds within the near future.

Statements that further research is needed on the biology (Nishimoto, 2000) and management (Filho, 2000) of *C. rotundus* is indicative that the battle is not yet won against this weed. Positive advances have been made in recent years on the chemical and biological control of sedges but are the Cyperaceae still among the world's worst weeds? The answer must be an unqualified yes.

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