

1 **An assessment of the effectiveness of a large, national-scale invasive alien**
2 **plant control strategy in South Africa**

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14 **ABSTRACT**

15 This paper presents an assessment of a large, national-scale alien plant control
16 program that has operated in South Africa for 15 years. We reviewed data from three
17 national-level estimates of the extent of invasion, records of the costs and spatial
18 extent of invasive species control operations, assessments of the effectiveness of
19 biological control, and smaller-scale studies. We identified the most important
20 invasive species in terrestrial biomes, and assessed how control efforts have
21 impacted on the extent of invasion of these species. We focussed on 18 alien taxa,
22 mainly trees, that were prominent invaders. Control costs over 15 years amounted to
23 US\$457 million, almost half of which was spent on 10 taxa, the most prominent
24 being invasive trees in the genera *Acacia*, *Prosopis*, *Pinus* and *Eucalyptus*. Despite
25 significant spending, control operations were in many cases applied to a relatively
26 small proportion of the estimated invaded area, and invasions appear to have
27 increased in many biomes, where they remain a serious threat. Our findings suggest
28 that South Africa's national-scale strategy to clear invasive alien plants should be
29 substantially modified if impacts are to be effectively mitigated. Rather than
30 attempting to control all species, and to operate in all areas, a more focused
31 approach is called for. This would include prioritizing both species and areas, and
32 setting goals and monitoring the degree to which they are achieved, within a
33 framework of adaptive management. A greater proportion of funding should also be
34 directed towards biological control, where the most notable successes have been
35 achieved.

36 **Keywords:** Adaptive management, biological control, biological invasions, ecosystem
37 services, invasive alien species, Working for Water

38

39 **1. Introduction**

40 Alien plant invasions are a large and growing threat to ecosystem integrity in
41 many parts of the world, where they change the structure and functioning of
42 ecosystems, with negative consequences for the conservation of biodiversity and the
43 delivery of ecosystem services (Mooney 2005). There are several examples of high-
44 level strategies to deal with the problem of invasive alien species, both at global
45 (McNeely *et al.* 2001) and national levels (Federal Interagency Committee 1998;
46 Anon. 1999). These strategies all call for reducing the risk of new introductions of
47 invasive species, the control of existing invasions to mitigate impact, and the
48 establishment of management and legislative capacity to guide implementation.
49 Interventions that give effect to national strategies are often a major component of
50 the management of terrestrial ecosystems (Wittenburg and Cock 2005), and
51 attempts to control invasive species can and have brought about significant levels of
52 mitigation (Simberloff *et al.* 2011).

53 In South Africa, the strategy over the past 15 years has been to implement a
54 large, national-scale, government-sponsored alien plant control program (van Wilgen
55 *et al.* 1998; 2011a; Koenig 2009). Known as 'Working for Water', the program has
56 adopted a comprehensive approach to alien plant control, characterised by several
57 distinguishing features. The program combines mechanical and chemical control of
58 all invasive alien plant species in targeted areas with the provision of employment to
59 people from impoverished rural communities as its main thrust. This has been
60 supplemented by (1) the development of biological control options that target
61 selected priority alien plant species (Zimmermann *et al.* 2004; Moran *et al.* 2005); (2)
62 the promulgation of legislation that requires landowners to deal with the problem
63 (van Wilgen *et al.* 2011a); and (3) the encouragement of systems of payment for

64 ecosystem services that will generate funding to support control programs (Turpie *et*
65 *al.* 2008). Few countries have implemented similar control programs, and we are not
66 aware of any that have assessed their effectiveness at a national scale over one and
67 a half decades.

68 When Working for Water was initiated in 1995, an attempt was made to quantify
69 the extent of invasions at a national scale (Versfeld *et al.* 1998), to provide inputs for
70 management planning (see, for example, Le Maitre *et al.* 2002), to assist in the
71 quantification of impacts (Le Maitre *et al.* 2000), and to serve as a baseline against
72 which to assess trends. Working for Water has since spent 3.20 billion rands
73 (expressed as 2008 rands, approximately 457 million US\$) on alien plant control.
74 Whether or not the correct, top-priority, species are being targeted, and whether or
75 not progress has been made in reducing the extent of invasions, remains unknown.
76 While Working for Water has kept records of expenditure per species and
77 geographic area since 2002, the ability to address questions regarding the
78 effectiveness of their operations is limited because the program has not implemented
79 an effective system of monitoring and evaluation (Levendal *et al.* 2008). A
80 preliminary assessment of progress (Marais *et al.* 2004) was made by comparing the
81 rate of clearing to the rough approximations of invaded area in 1996. Marais *et al.*
82 concluded that, at the prevailing rates of clearing, and depending on the species, it
83 would take between two and 83 years to clear the most important species, but with
84 the important albeit unrealistic assumption that no further spread would take place
85 during this time.

86 Working for Water has taken several steps to assess trends and changes in the
87 situation. These include the commissioning in 2008 of a second national-scale
88 assessment of the extent of invasion (Kotzé *et al.* 2010), providing ongoing financial

89 support to a national-scale atlas project (Henderson 2007), and supporting (or acting
90 as a catalyst for) several finer-scale research projects. The study reported in this
91 paper used information from all of the above sources to assess the effectiveness of
92 Working for Water in suppressing and controlling invasive alien plants in South
93 Africa, and we propose improvements that could increase efficacy and success.

94 **2. Methods**

95 *2.1 Studies by biome*

96 Working for Water is a national-level initiative in South Africa, operating in all
97 nine of the country's provinces and across all major terrestrial biomes. The country's
98 indigenous vegetation is diverse, including nine terrestrial biomes, and high levels of
99 endemism are a feature of several biomes (Mucina and Rutherford 2006). We used
100 biomes as a basis for our assessment, as each biome is characterised by particular
101 features (e.g. fire and rainfall regimes, and levels of herbivory), and is invaded by
102 distinctive suites of alien plant species (Table 1). Much of the natural vegetation
103 remains untransformed, and provides important ecosystem services in the form of
104 livestock production from rangelands, water production from mountain catchments,
105 and conservation and tourism benefits from protected and other areas. All of these
106 services are under considerable threat from invasive alien plants (van Wilgen et al.
107 2008a).

108 *2.2 Extent of invasions*

109 There have been three national-scale, and several smaller-scale, estimates of
110 the extent of alien plant invasion in South Africa, compiled over the past 15 years.
111 We used these estimates to identify the most important species involved and to

112 assess, within the limits of the data (see section 2.6) the extent to which they have
113 impacted on the terrestrial biomes of South Africa.

114 The first estimate was initiated in 1994 by the Southern African Plant Invaders
115 Atlas (SAPIA, Henderson 1998). SAPIA is an ongoing project, which aims to collate
116 information on the distribution and abundance of invasive and naturalized alien
117 plants in southern Africa. Initially, the atlas was populated with data collected during
118 roadside surveys, but was later broadened to accept inputs from volunteers, who
119 were supplied with survey sheets to ensure the standardization of inputs. By 2006,
120 the SAPIA database contained approximately 58 000 records of alien plant species
121 presence and abundance within quarter degree squares (a grid of approximately 25
122 x 25 km). Henderson (2007) used the SAPIA database to estimate a prominence
123 value for each species, calculated as $P_i = A_i/A + R_i/R$ where P_i = the prominence of
124 species i in a particular area, A_i = the abundance of species i , A = the abundance of
125 all species, R_i = the total number of records of species i and R = the total number of
126 records of all species.

127 The second estimate was made in 1996 (Versfeld et al. 1998; Le Maitre *et al.*
128 2000). Data on the extent and location of the areas invaded by all important invasive
129 alien plant taxa were obtained from a variety of sources for this survey, including
130 some detailed field mapping, mainly at a 1:250 000 scale, with some at 1:50 000 and
131 at 1:10 000. The species data were captured, together with estimates of their density
132 for each of the mapped areas, in a GIS database. The density class of each species
133 in each polygon was used to estimate condensed areas (the equivalent area with a
134 canopy cover of 100%). The authors of the survey noted that the findings were rough
135 approximations, and needed to be interpreted with caution because the results were
136 based on a data set that contained some important uncertainties.

137 A third estimate in 2008 mapped 27 alien plant taxa (Kotzé *et al.* 2010).
138 Species in the genera *Pinus* and *Eucalyptus* and some *Acacia* were mapped
139 collectively. Prior to the survey, the entire country (excluding most of the arid biomes
140 - Desert, Nama karoo, succulent karoo, and arid portions of the grassland and
141 savanna biomes - and the Kruger National Park) was divided into homogenous
142 environmental units (HEUs), based on unique combinations of three classes of
143 rainfall, soil depth, clay content in the B-horizon of the soil, and two classes of terrain
144 in each tertiary (3rd order) catchment. Those portions of HEUs that had been
145 transformed were excluded. The remaining portions of the HEUs were then sampled
146 at 32 330 points. Points were allocated to HEUs in proportion to their area, and then
147 located at random within HEUs. At each sample point, the percentage cover of the
148 three dominant alien plant taxa was estimated from low-flying fixed-wing light aircraft
149 or helicopters on 100 x 100m plots by observers who were familiar with invasive
150 species in the area. A second set of 25 260 sample points were located on a grid of
151 1600 x 1600m in a subsample of 205 quaternary (4th order) catchments (about 10%
152 of the country), and results from this survey were used to verify broad levels of
153 invasion detected in the national survey. Survey data were used to estimate mean
154 percentage cover and coefficient of variation for each of the taxa in each HEU in
155 each catchment. We converted these estimates to 100% equivalent cover
156 ("condensed ha") for comparison to other surveys, using the formula $C = d/100 \times A$,
157 where C is the area expressed as condensed ha, d is the density (% cover), and A is
158 the area in ha that was treated.

159

160 We obtained estimates of the extent of invasion per biome by creating
161 subsets of the spatial databases described above using Mucina and Rutherford's

162 (2006) biome boundaries. In the case of the SAPIA database, a biome-scale
163 analysis of the data was already available (Henderson 2007). Our analysis excluded
164 the arid portions of the grassland and savanna biomes, which were not covered by
165 Kotzé et al.'s (2010) survey. A recent estimate of the extent of invasion by *Prosopis*
166 species was available for the Northern Cape Province (which includes large portions
167 of the succulent karoo, Nama karoo, arid grasslands and arid savannas) (van den
168 Berg 2010). Control in these biomes has focussed almost entirely on *Prosopis*
169 species, so we restricted our assessment in these biomes to the clearing of *Prosopis*
170 species in the Northern Cape Province. A number of finer-scale studies were used to
171 provide insights into trends in the extent of invasion in South Africa, and into the
172 effectiveness of control operations. These included Esler *et al.* (2010) for *Hakea*
173 species in the fynbos biome, Moeller (2010) for *Pinus* species in the Eastern Cape
174 Province, and Otten (2010) for *Acacia cyclops* in the Western Cape Province.

175 *2.3 Selection of invasive alien plant taxa*

176 We focussed our assessment on the most important invasive alien plant taxa.
177 These taxa were defined as the top 10 in terms of area occupied in the estimates of
178 Le Maitre et al. (2000) and Kotzé *et al.* (2010), and the top 10 in terms of
179 prominence value as defined by Henderson (2007, see section 2.2). In addition, we
180 ranked taxa in each biome in terms of the cost of control, and included the highest-
181 ranked taxa that jointly accounted for at least 85% of control costs in any given
182 biome. Authorities for species names, and common names, are provided in Tables 1
183 and 2, or at first mention in the text for species not in Tables 1 or 2.

184 *2.4 Costs of control*

185 The costs of control have been recorded by Working for Water in a spatially-
186 explicit database since 2002 (Marais *et al.* 2004). All of Working for Water's control
187 operations are carried out by contractors. The records include the species treated
188 and the direct costs paid out to contractors. As the records do not contain Working
189 for Water's overheads, we assumed that overhead costs (funds spent by Working for
190 Water minus funds paid to contractors for each year) were distributed among taxa in
191 the same proportion as the expenditure on the control of individual taxa. The costs of
192 chemicals were not recorded in the contractor database, and we included these in
193 overheads. We further assumed that funds expended prior to 2002 (1995 – 2001)
194 were allocated to the control of individual species in the same proportions as funds
195 expended after 2002. Finally, we used the consumer price index to inflate all costs to
196 2008 rands to account for inflation (1 US\$ = approximately 7 South African rands).
197 We used 2008 as a base year to allow for direct comparisons between expenditure
198 and the estimates of invasion up to that year.

199 *2.5 Extent of control*

200 Working for Water's contractor database contains the following records for
201 each site: the species being treated, the area treated (captured spatially at a scale of
202 at least 1:15 000), and the density of the infestation (based on aerial canopy cover).
203 For each biome, we determined the area that had been treated for each of the
204 selected invasive alien plant taxa (including initial treatment, and all follow-up
205 treatments where applicable). Areas were expressed as equivalent to 100% canopy
206 cover ("condensed ha") using the formula $C = d/100 \times A$, where C is the area
207 expressed as condensed ha, d is the density (% cover), and A is the area in ha that
208 was treated.

209 *2.6 Trends in alien plant cover*

210 It is important to understand trends in alien plant cover to assess whether control
211 efforts are sufficient to stem the spread or reduce the degree of invasion by alien
212 plants or, if insufficient, to estimate the control effort that would be needed to bring
213 the species under control. Ideally, this should be done by comparing the degree of
214 invasion over time in successive estimates that use the same approach. However, in
215 our study, such direct comparisons were not possible because of the different
216 approaches used in making the estimates. We therefore assessed trends for the
217 most important alien plant species using estimates from the two national surveys (Le
218 Maitre et al. 2000 and Kotzé et al. 2010) and the estimates of extent of control, as
219 indicators and not as comparable estimates. The emergence of new, rapidly-
220 spreading invasive species was assessed using the rate of addition of records to the
221 SAPIA database. In addition post-release monitoring of biological control agents
222 provided further insights into the effectiveness of control (Klein 2011; Moran and
223 Hoffmann 2011).

224 **3. Results**

225 *3.1 Extent of invasions and prominent taxa*

226 Invasive alien plants were estimated to occupy approximately 1.736 million
227 condensed ha in 1996 (Le Maitre 2000). By combining the estimates of Kotzé et al.
228 (2010) and van den Berg (2010) (which are from mutually exclusive areas that
229 together cover most of the country), the estimated extent of invasion in 2008 was
230 approximately 1.813 million condensed ha. While these estimates are not directly
231 comparable (section 2.6) the similarity of the estimates suggest that invasions have
232 not decreased. Records in the SAPIA database indicate that alien plant invasions

233 occur throughout South Africa, but are concentrated in the southwestern, southern
234 and eastern coastal belts and the adjacent interior, which are also the areas of
235 highest rainfall (Henderson 2007).

236 We focussed on 18 invasive alien plant taxa in this assessment (Table 2). Of
237 these, 15 were identified by merging the lists of the 10 most important taxa in either
238 Le Maitre et al. (2000), Henderson (2007) or Kotzé et al. (2010). A further three
239 were added because, despite their lower prominence, they were targeted for clearing
240 and attracted a significant proportion of clearing costs in at least one biome. These
241 were *Acacia melanoxylon*, *Cereus jamacaru* and *Caesalpinia decapetala*, targeted
242 for control in forest habitats, moist savannas and the Indian Ocean coastal belt
243 respectively. Almost all prominent taxa (15) were either trees or shrubs (Table 2).

244 3.2 Costs of control

245 The costs of control by Working for Water between its inception in 1995 and
246 the end of 2008 amounted to 3.20 billion rands (expressed as 2008 rands). Most
247 (83%) of the funds were spent on the top 10 taxa, with the remainder divided among
248 95 less prominent taxa. The largest proportion of funding (1.05 billion rands) was
249 spent on the control of *Acacia mearnsii*. If this is added to the costs associated with
250 the closely-related wattle species *Acacia dealbata* (cost of 86.9 million rands), the
251 costs of control of these two species accounted for more than one third of the costs
252 of all alien plant control. A total of 323.3 million rands was spent on the next most-
253 targeted taxon (*Prosopis* species), while 290.5 and 214.1 million rands were spent
254 on *Pinus* and *Eucalyptus* species respectively. The remaining taxa in the top 10 (and
255 costs of control in millions of rands) were *Chromolaena odorata* (207.5), *Cereus*
256 *jamacaru* (155.5), *Lantana camara* (153.5), *Hakea* species (95.2) and *Solanum*

257 *mauritianum* (69.4). The number and identity of the taxa attracting the highest
258 clearing costs varied in the different biomes (Table 3).

259 3.3 Assessment of control achieved in biomes

260 3.3.1 Fynbos biome

261 Control efforts may have reduced the extent of invasion of some, but not all,
262 of the species selected for our assessment in the fynbos biome. A relatively small
263 proportion (12.6 and 9.6%) of the 2008 estimated extent of *Acacia cyclops* and *A.*
264 *saligna* respectively have been subjected to control treatments (Table 3), but the
265 species may have declined in abundance as a result of the combined effects of
266 significant but unrecorded clearing by firewood cutters (not accounted for in Working
267 for Water's records) and a substantial degree of biological control (Table 4; see also
268 Otten 2010). Similarly, there are indications that *Hakea* species have declined
269 because of historic (pre-1995) mechanical clearing, ongoing clearing by Working for
270 Water, and a substantial degree of biological control (Esler et al. 2010). Both *Acacia*
271 *longifolia* (Andr.) Willd. (long-leaved wattle) and *A. saligna* and were previously
272 considered to be among the five most important invasive plant species in the biome
273 (Macdonald and Jarman 1984). The extensive monocultures of large, 8-m tall *A.*
274 *saligna* trees that previously dominated lowland fynbos areas have almost
275 completely disappeared as a result of biological control using a rust pathogen, and
276 the species survives only as patchy, but still problematic, clusters of diseased shrubs
277 (Moran and Hoffmann in 2011). In the case of *A. longifolia*, biological control has
278 reduced the relative importance of the weed to no more than "an incidental or trivial
279 problem" (Moran and Hoffmann 2011).

280 On the other hand, there is no indication that the extent of invasion by either
281 *Acacia mearnsii* or *Pinus* species has decreased in the fynbos biome, despite
282 significant ~~spending on the problem areas having been treated~~. About 70% and 60%
283 of the estimated area of *A. mearnsii* and of *Pinus* in 1996 respectively had been
284 treated between 2002 and 2008 (and more before records began), yet these species
285 remain prominent. One study in the eastern fynbos biome (Moeller 2010) estimated
286 that the cover of invasive *Pinus* had more than doubled (from 13.4 to 28.7%)
287 between 1986 and 2007. Gains made in the control of *Hakea* species are being
288 offset by invasion by *Pinus* species, which are equally successful invaders of the
289 same areas. Biological control may become more effective in future as the agents on
290 *Acacia mearnsii* spread and deplete seed loads, but no such solution is available for
291 *Pinus* (Table 4). In particular, the rugged and inaccessible mountain areas are most
292 vulnerable to invasion by *Pinus* species, and this poses the most significant threat to
293 the integrity of fynbos ecosystems (Hoffmann et al. 2011; Kraaij et al. 2011).

294 3.3.2 Grassland biome

295 Most of the control effort in grassland has been focussed on two tree taxa
296 (*Acacia* and *Eucalyptus* species, Table 3). About 20% of the 2008 estimated area of
297 the *Acacia* invasions has been subjected to control, compared to a very small
298 proportion (3.4%) of the *Eucalyptus* species. There appears to be no detectable
299 decline in the estimated extent of invasion by *Acacia* species between 1996 and
300 2008, suggesting that control operations are may not be keeping pace with invasion
301 rates. Both *Salix babylonica* and *Populus* species (prominent invaders of riparian
302 zones) received hardly any control, and appear to have increased. In addition, the
303 grassland biome is vulnerable to invasion from non-woody plants. These were not
304 included in our assessment as they have not been subjected to any significant

Comment [U@1]: Treatment has been localised, only 4% of Versfeld "extent"

305 degree of control. For example, several species in the genus *Rubus* (thorny shrubs),
306 and the herbaceous *Cirsium vulgare* (Savi) Ten. (Scotch thistle) are prominent
307 invaders of grasslands (Henderson 2007). In addition, the perennial herb
308 *Campuloclinium macrocephalum* (Less.) D.C. (pompom weed) has recently
309 undergone spectacular expansion in grasslands. Records from the SAPIA database
310 show that it spread from 48 to 93 quarter degree squares between 2005 and 2010.
311 Grasslands thus remain under significant threat from invasions despite considerable
312 clearing efforts.

313 3.3.3 Savanna biome

314 Alien plant control efforts in the savanna biome were focussed on more taxa
315 than other biomes (Table 3). Species of Cactaceae (including *Cereus jamacaru*)
316 appear to have declined (Table 3), but much of this may be due to biological control
317 rather than mechanical clearing. Despite spending over 444 million rands on the
318 remaining prominent taxa, it was only possible to treat a relatively small proportion
319 (4.3 – 38%) of their estimated 2008 invasions. The exception was *Lantana camara*,
320 where 88% of the 2008 estimated area was treated, and the extent of invasion may
321 have declined. For other species, notably *Acacia mearnsii* and *Chromolaena*
322 *odorata*, large increases between the 1996 and 2008 estimates of invaded area
323 suggest that the extent of invasion may have increased in spite of control efforts.
324 New invaders are also emerging in savannas, including *Tecoma stans* (L.) Kunth.
325 (yellow bells), an ornamental shrub or small tree, that has more than tripled its extent
326 from 28 known quarter degree squares in 1996 to 86 quarter degree squares in
327 2011.

328 3.3.4 Forest biome

329 Alien plant control operations in the forest biome focussed on trees in the
330 genera *Acacia*, *Eucalyptus* and *Pinus* (Table 3). Forests only cover 0.38% of South
331 Africa (Table 1), with a scattered distribution. The scale of mapping used in various
332 surveys is relatively coarse compared to the distribution of forests, and it is therefore
333 not possible to draw confident conclusions regarding the success of control
334 operations in the forest biome.

335 3.3.5 Albany thicket biome

336 Alien plant control operations in the thicket biome focussed on a single
337 species (*Acacia mearnsii*), which accounted for > 85% of the control costs. The
338 estimates of the invaded area in 1996 and 2008 suggest that invasions may have
339 increased. Such an increase would not be surprising, given that only a small
340 proportion of the estimated invaded area (3%) has been treated to date, and that one
341 of the two effective biological control agents has only recently been released
342 (Impson et al. 2008), and is not yet present in the thicket biome. It appears therefore
343 that not much progress has been made with the control of *Acacia mearnsii* in the
344 thicket biome.

345 3.3.6 Indian Ocean Coastal biome

346 *Chromolaena odorata* is the most dominant invasive species in this biome,
347 and it has received the bulk of funding for control costs (Table 3). Although a large
348 proportion (80%) of the estimated invaded area has been treated over the past 15
349 years, there is no indication that the extent of the invasion has changed. A
350 considerable effort has been made to find biological control agents for this significant
351 invader species (31 agents have been considered, and 5 released, of which one
352 causes “considerable” damage to the plant, Klein 2011). The overall degree of

353 biological control achieved has yet to be determined, but is still localised and
354 inconsequential (Table 4). *Chromolaena odorata* therefore remains a large and
355 growing threat to ecosystem integrity in the biome.

356 3.3.7 Arid biomes

357 Alien plant control operations in all arid areas (the Nama karoo, succulent karoo,
358 desert, and arid portions of savanna and grassland biomes in the Northern Cape
359 Province) focussed on a single taxon (*Prosopis* species), which accounted for > 85%
360 of the control costs in all arid biomes. Despite expenditure of 219 million rands, the
361 control was only applied to a relatively small proportion (7%) of the estimated
362 invaded area (Table 3). It also appears that *Prosopis* invasions are increasing at an
363 exponential rate despite clearing efforts. The estimated extent of invasion grew by
364 363% between 1990 and 2007, from about 77 000 condensed ha in 1990, to
365 147 000 ha in 2002, 203 000 ha in 2003 and 360 000 ha in 2007 (van den Berg
366 2010). *Prosopis* trees have some useful properties, and for this reason biological
367 control options have been limited to seed-feeding insects, which only achieve a
368 negligible degree of control (Table 4). Economic studies have indicated, however,
369 that the rapid expansion of *Prosopis* will result in the value of negative impacts
370 exceeding the value of benefits in the near future, suggesting that a different
371 approach to the control of *Prosopis* is needed (Wise et al. in press), and that the
372 threat of ongoing invasion by *Prosopis* species remains a significant concern.
373 Emerging invaders in arid biomes include the torch cactus, *Echinopsis spachiana*,
374 which has spread from 39 quarter degree squares in 1996 to 75 quarter degree
375 squares in 2011, almost doubling in area. The species has the potential to become a
376 serious threat to ecosystem integrity in arid areas.

377 4. Discussion

378 4.1 The value of control

379 Invasive alien plants are often associated with serious negative economic
380 consequences (Pimentel 2002, Perrings et al. 2010), and preventing or reversing
381 these impacts is the primary goal of invasive alien plant control programs. In South
382 Africa, the economic cost of alien plant invasions at current levels of invasion was
383 estimated to be 6.5 billion rands annually (2008 values, De Lange and van Wilgen
384 2010); the prevention of such losses, especially those associated with loss of water
385 resources was the primary reason for initiating Working for Water (van Wilgen et al.
386 2011a). Our assessment suggests, however, that the primary goal of preventing the
387 erosion of ecosystem services is not being met at a national scale. The control
388 operations have in many cases only reached a small percentage of the estimated
389 invaded areas (for example, 7% of the estimated area under *Prosopis* invasions in
390 arid areas, and 16% of *Acacia mearnsii* invasions in the savanna and grassland
391 biome). Alternately, for many taxa where control operations have reached a
392 significant portion of the invaded area, the impact has not been large. For example
393 about half of the area under *Pinus* invasions in the fynbos has been subjected to
394 control, with little apparent impact on the overall state of invasion. Similarly,
395 *Chromolaena odorata* invasions have remained prominent, or grown, despite a
396 significant proportion having been treated in the moist savanna and Indian Ocean
397 coastal biomes. Although progress has been made with the suppression of several
398 invasive taxa, it appears that most biomes remain under threat from several
399 prominent species – notably *Pinus* in fynbos, *Acacia* in grassland, savanna and
400 thicket, *Prosopis* in arid areas, *Campuloclinium macrocephalum* in grassland and
401 *Chromolaena odorata* in the Indian Ocean coastal belt. The overall negative impacts

402 of invasive alien plants may continue to grow therefore, unless more effective
403 solutions can be found.

404 While the above summary points to a serious problem, it does not mean that
405 control efforts to date have been entirely without benefit. Had the control not taken
406 place, the situation would undoubtedly have been worse. Progress appears to have
407 been made with the mechanical clearing of some species (Table 3), while others
408 have been reduced in extent and impact by a combination of mechanical and
409 biological control (Esler et al. 2008), or, in some cases, biological control alone (Klein
410 2011). One estimate suggested that, had no control been carried out, the annual
411 economic losses from alien plant invasions would have been as high as 41.7 billion
412 rands (instead of 6.7 billion rands), further, and that a significant proportion of these
413 savings (between 5 and 75%, depending on the group of plants) arose from the
414 biological control of invasive alien plants (De Lange and van Wilgen 2010). In
415 addition, Working for Water was able to create 20 000 employment opportunities
416 annually over 15 years in impoverished areas, that would not have been there had
417 the program not existed.

418 In some areas, where control programs have focussed on smaller areas and
419 adhered to systematic control schedules, significant progress has been made. For
420 example, invasive alien plants have been eliminated from large sections of the
421 formerly densely-invaded Table Mountain National Park (BWvW, personal
422 observation). Nonetheless, our assessment suggests that the strategic approach of a
423 comprehensive program that attempts to target many invasive alien plant species in
424 many areas, using poverty-relief funding, needs to be reassessed if progress is to be
425 made.

426 *4.2 Options for increasing effectiveness*

427 Working for Water's strategic plan (Anon. 2007) calls for, among other things, the
428 prioritization of invasive alien plant species for management action, the development
429 of indicators to underpin a monitoring program, and the implementation of such a
430 program. A start has been made with the prioritization exercise (Nel et al. 2004; van
431 Wilgen et al 2007; 2008b), but monitoring and evaluation has not been adequately
432 resourced to date. The ongoing attempts to control a wide range of invasive alien
433 plant species in the absence of adequate co-ordination and monitoring has been
434 described as "a strategy of hope" (van Wilgen et al. 2011b). Key missing elements
435 include (1) adequate integration of management interventions (mechanical clearing
436 operations, biological control, and legislative compliance); (2) clear, time-based
437 targets; and (3) protocols for adapting approaches as new information comes to light
438 (van Wilgen et al. 2011b). Several options are available to increase effectiveness by
439 making revisions to the strategic approach that has been adopted to date. These
440 include:

441 (1) Investing an appropriate proportion of funds into the prioritization of control
442 operations, planning, monitoring and evaluation. Working for Water has
443 arguably initiated too many projects, and targeted too many species in too
444 many areas, to be effective. One study (Roura-Pascual et al. 2009) concluded
445 that "considerable progress in controlling the spread of invasive alien plants in
446 fynbos ecosystems could be achieved by better coordination of management
447 practices and by improving the quality of species distribution data". By setting
448 clear goals, and targeting fewer species in selected priority areas, the
449 available funds could almost certainly be used more effectively.

450

451 (2) Improved integration of mechanical and biological control. These two forms of
452 control have seldom been deliberately co-ordinated, as they should be (Wood
453 2011). Where this has happened (see, for example Hoffmann et al. 1998),
454 significant benefits have been reaped. The early release of biological control
455 agents to allow establishment, and to affect a reduction in seed output and
456 some suppression of plant growth or populations, before mechanical clearing
457 proceeds can make a significant contribution to the success of the entire
458 operation.

459
460 (3) Improving efficiency and professionalism. Working for Water's strategy of
461 investing in the development of relatively inexperienced contractors, to create
462 management capacity, and employing a largely untrained workforce, to
463 alleviate poverty, has brought advantages and disadvantages. The
464 advantages include the delivery of benefits to indigent people in rural areas
465 where few other employment opportunities exist, and gaining political support,
466 and thus substantial funding. The disadvantages include inefficiencies in
467 control operations. Working for Water's records show that up to 9 follow-up
468 visits are required for the control of *Acacia* species, and at least part of this is
469 due to a lack of diligence in the application of standard control procedures.
470 The expenditure of R155.5 million rands on the mechanical clearing of *Cereus*
471 *jamacaru*, when biological control options were available to achieve complete
472 control at a small fraction of the cost (Table 4), provides another example of a
473 significant inefficiency that could arguably have been avoided had a more
474 professional approach been adopted.

475

476 (4) Directing a greater proportion of the available funding to biological control
477 research, where many successes have been registered (Table 4) and where
478 many more are possible. Currently, spending on biological control is far lower
479 than on other forms of control (about 3% of the total funds available) despite
480 the significantly better returns on investment from biological control. In their
481 review of the costs and benefits of biological control, van Wilgen and De
482 Lange (2010) noted that “Mechanical and chemical forms of control, while
483 effective in the short term, and often essential components of integrated
484 control, are at best a holding action. Invasive alien plant species are never
485 eradicated by mechanical and chemical clearing, and will re-invade cleared
486 areas, requiring constant ongoing containment. The likelihood that funding for
487 such operations can be maintained at the necessary levels in perpetuity is
488 low. Biological control solutions therefore should be sought and implemented
489 for as many weed species as possible, freeing up scarce resources for the
490 control of invasive plant species for which no biological control options are
491 available”.

492
493 (5) Promoting a more widespread use of schemes of payment for ecosystem
494 services. Some water utilities and municipalities have contracted Working for
495 Water to control invasive alien plants in their water catchments, using
496 payments for services (in this case water supply to users, Turpie et al. 2008).
497 However, this practice is not widespread enough, and should be encouraged
498 or even made mandatory, as the funding for control operations would both
499 increase and be placed on a more sustainable basis.

500

501 (6) Dealing effectively with invasions on privately-owned land. Working for
502 Water's has provided assistance to private landowners by clearing land, with
503 the explicit understanding that landowners would then prevent re-invasion of
504 cleared sites. By and large, landowners have not honoured such agreements,
505 frequently citing Working for Water's inefficiencies (that effectively leave the
506 land in an invaded state – see point 3 above) as a justification for not taking
507 responsibility for ongoing maintenance. As most land in South Africa is in
508 private ownership, a solution to this problem would be essential to the
509 retention of gains made through initial clearing.

510
511 (7) Dealing with conflicts. Several important invasive alien plant species (notably
512 trees in the genera *Pinus*, *Acacia* and *Prosopis*) are conflict species, as they
513 bring both benefits and negative impacts. Studies have shown the economic
514 benefits gains often exceeded by negative impacts, and that placing
515 constraints on control options to protect benefits is not economically justifiable
516 (De Wit et al. 2001; Hoffmann et al. 2011; Wise et al. in press). In such cases,
517 political courage and sustained commitment will be required to ensure
518 sustainable outcomes (through, for example, allowing expansion of biological
519 control options to more damaging agents, van Wilgen et al. 2011b).

520
521 (8) Adopting a framework of adaptive management (Wilhere 2002; Stankey et al.
522 2005) to allow for ongoing improvement of management in a complex
523 environment where the outcomes of management cannot be accurately
524 predicted. Adaptive management will require changes to Working for Water's
525 approach, including setting clear and achievable targets, introducing an

526 effective monitoring program to assess progress towards these targets, and
527 accepting the flexibility to adapt approaches should targets not be met.

528 Gaining control of invasive species, and reducing their substantial impacts, is an
529 extremely important component of natural resource management. Given the
530 indications presented here that impacts have continued to grow in many areas
531 despite significant investments in control suggests that changes to the strategy are
532 needed if significant successes are to be achieved in controlling populations of
533 invasive alien plants in South Africa.

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Table 1

715 Features of the terrestrial biomes in South Africa, and the major invasive alien species in each biome. Data are from Mucina and Rutherford (2006) and Henderson (2007)

Biome	Extent (km ²)	Proportion of biome remaining untransformed(%)	Features	Prominent invasive alien plant species
Fynbos	83 964	69	Mediterranean-climate, fire-prone, 1 – 2 m tall shrublands on nutrient-poor soils. High levels of diversity and endemism among plant species.	Trees and shrubs in the genera <i>Acacia</i> (wattles), <i>Pinus</i> (pines) and <i>Hakea</i> (shrubs in the family Proteaceae).
Grassland	354 953	65	Short-stature, relatively species-rich vegetation dominated by grasses, with few other life-forms present. Prone to frequent fire and subject to high levels of grazing.	Important trees include wattles (<i>Acacia</i> species), willows (<i>Salix</i> species), poplars (<i>Populus</i> species) and gums (<i>Eucalyptus</i> species), notably along rivers. Shrubs include <i>Rubus</i> species (brambles), <i>Pyracantha</i> species (firethorns) and cacti (<i>Opuntia</i> species).
Savanna	412 544	77	Characterised by the co-dominance of trees and grasses. The proportion of trees to grasses is determined largely by four interacting factors: soil fertility, rainfall, fire and grazing pressure. Our analysis divided savanna into arid and moist areas to accommodate comparisons to	Invasive species are dominated by the shrubs <i>Chromolaena odorata</i> (L.) R.M.King & H.Rob. (triffid weed) and <i>Lantana camara</i> L. (lantana). Important invasive trees include wattles (<i>Acacia</i> species), <i>Melia azederach</i> L. (syringa), <i>Solanum mauritianum</i> Scop. (bugweed), <i>Psidium guajava</i> L. (guava) and <i>Jackaranda mimosifolia</i> D.Don. (jackaranda). Trees in the genus <i>Prosopis</i> (mesquite) are predominant in

			other surveys that used similar divisions.	arid parts.
Albany thicket	29 127	88	Dense, woody, semi-succulent and thorny vegetation, 2 – 3 m tall. Essentially fire-free due to low amounts of dead dry material and high proportion of succulents.	Invasive succulents, mainly cacti (<i>Opuntia</i> and related genera).
Nama karoo	248 728	98	Low, dwarf shrublands, with co-occurring grasses, succulents, geophytes and annuals. Small trees occur along drainage lines.	Trees in the genus <i>Prosopis</i> (mesquite). The shrub <i>Atriplex lindleyi</i> Moq. subsp. <i>inflata</i> (F.Müll.) P.G.Wilson (sponge-fruit salt-bush) and the cactus <i>Opuntia ficus-indica</i> (L.) Mill. (sweet prickly pear) are also predominant. The tree <i>Schinus molle</i> L. (pepper tree) is becoming increasingly widespread.
Succulent karoo	83 283	95	Highly diverse low dwarf shrublands with many succulents and low cover. The world's only arid biodiversity hotspot.	Trees in the genera <i>Acacia</i> (wattles), <i>Prosopis</i> (mesquite) and <i>Populus</i> (poplars), and the shrubs <i>Nicotiana glauca</i> Graham (wild tobacco) and <i>Atriplex lindleyi</i> Moq. subsp. <i>inflata</i> (F.Müll.) P.G.Wilson (sponge-fruit salt-bush) and <i>A. nummularia</i> Lindl. (old man saltbush). The cactus <i>Opuntia ficus-indica</i> (L.) Mill. (sweet prickly pear) is also predominant.
Indian Ocean coastal belt	14 282	51	Mixed vegetation characterised by juxtaposed fire-prone grasslands and fire-free forests.	The herbaceous shrubs <i>Chromolaena odorata</i> and <i>Lantana camara</i> are the most important invasive species. Additional species include <i>Caesalpinia decapetala</i> , <i>Cestrum laevigatum</i> and <i>Psidium guajava</i> L. (guava).
Forest	4731	94	Multilayered vegetation dominated by evergreen trees, ranging in height from 3m to 30 m. Occurs as scattered, fire-free patches of varying size.	Dominant invasive trees include wattles (<i>Acacia</i> species) and <i>Solanum mauritianum</i> Scop. (bugweed). <i>Chromolaena odorata</i> (L.) R.M.King & H.Rob. (triffid weed) and <i>Lantana camara</i> are important invasive shrubs.

Desert	7166	99	Dry areas (< 70mm mean annual rainfall) with sparse perennial vegetation of < 10% cover.	Invasions of <i>Prosopis</i> (mesquite) trees in dry river beds.
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Table 2

720 Prominent invasive alien plant taxa in South Africa, and the cost of control by Working for Water between 1995 and 2008 for each taxon. Clearing costs are expressed as 2008-equivalent rands (1 US\$ = approximately 7 South African rands).

Invasive alien plant taxon	Growth form	Rank in terms of area occupied (Le Maitre et al. 2000).	Rank in terms of area occupied (Kotzé et al. 2010).	Rank in terms of prominence value (Henderson 2007).	Clearing cost (millions of rands)
<i>Acacia cyclops</i> A.Cunn. ex G.Don (rooikrans)	Evergreen tree	1	7	4	63.2
<i>A. dealbata</i> Link (silver wattle)	Evergreen tree	12	1 (grouped with other wattle species)	10	86.9
<i>A. mearnsii</i> De Wild. (black wattle)	Evergreen tree	3	1 (grouped with other wattle species)	1	1055.4
<i>A. melanoxylon</i> R.Br. (blackwood)	Evergreen tree	26	25	25	31.8
<i>A. saligna</i> (Labill.) H.L.Wendl. (Port Jackson Willow)	Evergreen tree	4	8	2	56.5
<i>Caesalpinia decapetala</i> (Roth) Alston (Mauritius thorn)	Evergreen shrub	16	18	27	31.9
<i>Cereus jamacaru</i> DC. (queen of the night)	Spiny succulent tree	Not reported	17	51	155.5
<i>Chromolaena odorata</i> (L.) R.M.King & H.Rob. (triffid weed)	Scrambling shrub	14	4	11	207.5
<i>Eucalyptus</i> species (gum)	Evergreen trees	11	2	13	214.1

trees)					
<i>Hakea sericea</i> Schrad. & J.C.Wendl. (silky hakea)	Evergreen shrub	10	11	41	95.2
<i>Lantana camara</i> L. (lantana)	Scrambling shrub	9	12	3	153.5
<i>Melia azederach</i> L. (syringe)	Deciduous tree	8	13	9	50.9
Cactaceae	Spiny, succulent trees and shrubs	7	5	5	40.9
<i>Pinus</i> species (pine trees)	Evergreen trees	6	3	14	290.5
<i>Populus</i> species (poplar trees)	Deciduous trees	24	6	7	26.7
<i>Prosopis</i> species (mesquite)	Evergreen trees	2	Not reported	12	323.3
<i>Salix babylonica</i> L. (weeping willow)	Evergreen tree	25	10	8	4.0
<i>Solanum mauritianum</i> Scop. (bugweed)	Evergreen shrub or small tree	5	9	6	69.4

Table 3

725 Estimates of area occupied at different times, area subjected to control, and cost of clearing for prominent invasive alien plant taxa (see Table 2) in major terrestrial biomes in South Africa. Clearing costs are expressed as 2008-equivalent rands. Estimates for area occupied in 1996, and 2007 are from Le Maitre et al. (2000) and Henderson (2007) respectively. Estimates for 2008 are from van den Berg (2010) for *Prosopis* and Kotzé et al. (2010) for all other taxa.

Biome	Invasive alien plant taxon	Estimated area occupied			Control effort	
		In 1996 (condensed ha x 1000)	In 2007 (prominence value)	In 2008 (condensed ha x 1000, +/- CV%)	Area treated between 2002 and 2008 (condensed ha x 1000)	Cost of treatment between 1995 and 2008 (millions of rands)
Fynbos	<i>Acacia cyclops</i>	285.6	27.2	48.4 (\pm 12.1)	6.1	62
	<i>A. mearnsii</i>	45.6	31.5	27.5 (+/-14.1)	32.1	488
	<i>A. saligna</i>	92.3	30.40	45.6 (+/- 12.1)	4.4	57.5
	<i>Hakea</i> species	39.6	3.84	36.6 (+/-13.6)	12.6	102
	<i>Pinus</i> species	50.4	11.22	58.5 (+/-14.0)	29.5	240
	<i>Populus</i> species	3.2	3.19	1.9 (+/- 12.1)	0.7	9.2
Grassland (excluding arid areas)	<i>Acacia dealbata</i> and <i>A. mearnsii</i>	110.1	42.2	310.8 (+/-14.0)	62.2	470
	<i>Eucalyptus</i> species	118.9	7.35	157.6 (+/-15.1)	5.5	65
	<i>Populus</i> species	5.8	14.19	43.4 (+/- 14.8)	0.9	11.9
	<i>Salix babylonica</i>	6.0	17.30	34.9 (+/- 14.8)	0.4	4.9
	<i>Solanum mauritianum</i>	41.3	10.6	7.1 (+/-13.6)	4.3	60
Moist savanna	<i>Acacia mearnsii</i>	28.4	10.2	103.7 (+/- 13.6)	4.5	56
	<i>Cereus jamacaru</i>	21.9	1.99	10.2 (+/- 16.2)	32.7	156
	<i>Cactaceae</i> species	47.0	11.76	18.7 (+/- 12.0)	33.3	179.6
	<i>Chromolaena odorata</i>	23.7	14.2	73.3 (+/- 14.1)	12.7	86

	<i>Eucalyptus</i> species	25.4	4.0	70.4 (+/- 14.9)	5.8	78
	<i>Lantana camara</i>	40.3	20.6	22.5 (+/- 14.2)	19.8	128
	<i>Melia azedarach</i>	58.8	12.00	10.0 (+/- 15.1)	3.8	29
	<i>Solanum mauritianum</i>	38.1	10.6	24.8 (+/- 15.5)	4.9	67
Forest	<i>Acacia melanoxylon</i>	1.0	14.2	0.1 (+/- 14)	0.3	7
	<i>A. mearnsii</i>	1.1	16.7	2.1 (+/- 11.4)	0.9	12
	<i>Eucalyptus</i> species	0.1	7.23	1.9 (+/- 13.6)	0.2	3
	<i>Pinus</i> species	0.2	7.86	4.2 (+/- 12.1)	0.5	5
Albany thicket	<i>Acacia mearnsii</i>	10.5	No data	17.7 (+/- 11.6)	0.4	61
Indian Ocean Coastal Belt	<i>Caesalpinia decapetala</i>	0.3	No data	0.4 (+/- 12.3)	0.2	7
	<i>Chromolaena odorata</i>	19.3	No data	19.0 (+/- 14.8)	15.4	96
	<i>Lantana camara</i>	8.0	No data	6.0 (+/- 12.0)	2.0	14
Nama Karoo (Northern Cape only)	<i>Prosopis</i> species	104.5	78.8	252.8	14.9	134
Succulent karoo (Northern Cape only)	<i>Prosopis</i> species	52.0	8.9	32.1	3.7	19
Arid savanna (Northern Cape only)	<i>Prosopis</i> species	51.3	No data	51.3	5.3	49
Desert	<i>Prosopis</i> species	3.9	No data	7.8	1.4	17

Table 4

Prominent alien plant taxa in South Africa (see Table 2), and the degree of biological control achieved for each taxon. The degree of control was assessed as follows: Complete: no other control measures are needed to reduce the weed to acceptable levels.

735 Substantial: Other methods are needed to reduce the weed to acceptable levels, but less effort is required. Negligible: despite damage, control of the weed remains entirely reliant on the implementation of other control measures (after Klein 2011).

Invasive alien plant taxon	Biological control agents released	Degree of control achieved	Notes	Key references
<i>Acacia cyclops</i>	Seed feeder and flower galler	Substantial	Predicted that “there will be a substantial and sustained decline in abundance” of this species over time, as a result of depleted soil-stored seed banks.	Moran and Hoffmann (2011) Impson et al. (2011)
<i>A. dealbata</i>	Seed feeder	Not determined	Should agents reduce seed output substantially, mechanical clearing would still be needed to eliminate existing stands	Impson et al. (2011).
<i>A. mearnsii</i>	Seed feeder and flower galler	Not determined	Should agents reduce seed output substantially, mechanical clearing would still be needed to eliminate existing stands. Conflict of interest species, and biological control restricted to agents that do not damage the vegetative parts of the plant.	Impson et al. (2011) van Wilgen et al. (2011b)
<i>A. melanoxylon</i>	Seed feeder	Substantial	Control agents reduce seed output substantially, but mechanical clearing needed to eliminate existing stands. Conflict of interest species, and biological control restricted to agents that do not damage the vegetative parts of the plant.	Impson et al. (2011)
<i>A. saligna</i>	Seed feeder and fungal gall former	Substantial	Seed production and plant vigour both considerably reduced, resulting in significant declines in dominance.	Impson et al. (2011) Moran and Hoffmann (2011)
<i>Caesalpinia decapetala</i>	Seed feeder	Negligible	This species was not considered as a high priority for biological control research by Working for Water	Byrne et al. (2011)
<i>Cereus jamacaru</i>	Stem sucker and	Complete	Mechanical clearing has continued despite the	Paterson et al. (2011)

	stem borer		availability of highly effective biological control (Table 3).	
<i>Chromolaena odorata</i>	Leaf miner, stem borer and three species of leaf feeders	Not determined	One leaf feeder found to inflict considerable damage in very localised areas, but, overall, weed populations have not been suppressed	Zachariades et al. (2011a).
<i>Eucalyptus</i> species	None	Not applicable	Many <i>Eucalyptus</i> species are not aggressively invasive, and this group has not been considered for biological control.	None
<i>Hakea sericea</i>	Stem borer, seed feeder, stem gummosis disease, leaf and shoot borer, flowerbud feeder and green-seed feeder	Substantial	<i>Hakea sericea</i> appears to be declining as a result of the combined effects of mechanical clearing and biological control	Gordon and Fourie (2011) Esler et al. 2010.
<i>Lantana camara</i>	Thirteen agent species released and established. Damage to flowers, leaves and roots	Negligible to substantial control, depending on plant variety.	This species forms hybrids, which complicates the search for biological control options.	Urban et al. (2011)
<i>Melia azedarach</i>	None	Not applicable	The exact area of origin of <i>Melia azedarach</i> is not known, so a source of potential biological control agents cannot be located.	None
Cactaceae	Cladode borers, cladode suckers, stem suckers and stem borers.	Complete (3 species) Substantial (8 species) Negligible (1 species) Not determined (2 species)	Fourteen species of Cactaceae (excluding <i>Cereus jamacaru</i>) have been subjected to biological control, including the genera <i>Austrocylindropuntia</i> , <i>Cylindropuntia</i> , <i>Harrisia</i> , <i>Opuntia</i> and <i>Pereskia</i> .	Paterson et al. (2011)
<i>Pinus</i> species	None	Not applicable	Conflict of interest species, and biological control	Hoffmann et al. 2011.

			research restricted to seed feeders	
<i>Populus</i> species	None	Not applicable		None
<i>Prosopis</i> species	Seed feeders	Negligible	Conflict of interest species, and biological control restricted to seed feeders (Wise et al. in press).	Zachariades et al. (2011b)
<i>Salix babylonica</i>	None	Not applicable		None
<i>Solanum mauritianum</i>	Flowerbud feeder and leaf sucker	Negligible		Olckers 2011