



HAL
open science

Plant phenological research enhances ecological restoration

Elise Buisson, Swanni Alvarado, Soizig Le Stradic, Leonor Patricia C. Morellato

► **To cite this version:**

Elise Buisson, Swanni Alvarado, Soizig Le Stradic, Leonor Patricia C. Morellato. Plant phenological research enhances ecological restoration. *Restoration Ecology*, 2017, 25 (2), pp.164 - 171. 10.1111/rec.12471 . hal-01777942

HAL Id: hal-01777942

<https://hal.science/hal-01777942>

Submitted on 25 Apr 2018

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

1 **Title**

2 **Plant phenological research enhances ecological restoration**

3

4 **Authors**

5 Elise Buisson^{1*}, Swanni T. Alvarado^{2,4}, Soizig Le Stradic^{3,4}, Leonor Patricia C. Morellato⁴

6 ¹ *Institut Méditerranéen de Biodiversité et d'Ecologie (IMBE), Université d'Avignon et des Pays de*
7 *Vaucluse, CNRS, IRD, Aix Marseille Université, IUT d'Avignon, Agroparc BP 61207, 84911 Avignon*
8 *cedex 9, France.*

9 * *corresponding author : elise.buisson@univ-avignon.fr Phone: +33 490 84 38 58 ; Fax: +33 490 84 38*
10 *07*

11 ² *Instituto de Geociências e Ciências Exatas, UNESP – Univ Estadual Paulista, Departamento de*
12 *Geografia, Ecosystem Dynamics Observatory. Caixa postal 178, Av. 24A, 1515. CEP 13506-900. Rio*
13 *Claro, SP, Brazil. 13506-900. swanni_ta@yahoo.es*

14 ³ *Biodiversity and Landscape Unit, Gembloux Agro-Bio Tech, University of Liege, Passage des*
15 *Déportés, 2, 5030 Gembloux, Belgium. soizig.lestradic@gmail.com*

16 ⁴ *Instituto de Biociências, UNESP – Univ Estadual Paulista, Departamento de Botânica, Phenology*
17 *Laboratory, São. Avenida 24A, 1515. CEP 13506-900, Rio Claro, SP, Brazil.*
18 *soizig.lestradic@gmail.com; pmorella@rc.unesp.br*

19

20 **Author contributions**

21 EB, LPCM designed the study. EB, STA, SLS, LPCM targeted the research question; EB performed the
22 review and wrote the manuscript; EB, STA, SLS, LPCM contributed to writing and revising the
23 manuscript; EB, LPCM found the funding to carry out the study.

24

25 **Key words:** exotic species, genetic provenance, germination, restoration management, monitoring,
26 phenology, seed harvest, seed production, seed mixes, species interactions

27

28

29 **Abstract**

30 While phenology data (the timing of recurring biological events) has been used to explain and predict
31 patterns related to global change, and to address applied environmental issues, it has not been
32 clearly identified as pertinent for restoration. This opinion paper thus aims to raise awareness of the
33 potential of phenology to enhance the quality of restoration projects and ecological restoration
34 theory. We based our analysis on a systematic literature survey carried out in February 2014,
35 searching the words “phenology” or “phenological” in books dealing with restoration, the term
36 “phenolog*” in the journal *Restoration Ecology*, and the terms “restoration” and “phenolog*” in the
37 database Web of Science until February 2014. We finally selected 149 studies relevant to our goals,
38 and first classified them according to the context in which phenology was addressed. We then
39 analyzed them within the framework of the five key steps of restoration projects: 1) the reference
40 ecosystem, 2) biotic resources, 3) restoration methods, 4) monitoring, and 5) adaptive management.
41 The literature survey showed that phenological information improved decision-making in the few
42 restoration projects in which it was incorporated. We thus advocate taking phenological data into
43 account at all stages of restoration when appropriate: from the acquisition of baseline data on the
44 reference ecosystem to treatment design, and from restoration action planning and timing to
45 monitoring. Phenological data should at minimum be collected for sown, keystone, dominant and/or
46 rare species to improve restoration quality. Phenology studies and monitoring should be promoted in
47 future restoration guidelines.

48

49 **Running title:** Phenology and restoration ecology

50

51

52 **Implications for practice**

53 • Phenology is an integrative environmental science which should be incorporated in ecological
54 restoration project guidelines. Concurrently, restoration can provide new insights into phenological
55 drivers and patterns.

56 • Restoration often requires the use of plants, and phenological data helps identify which species is
57 most suitable and when and where locally adapted seeds can be acquired.

58 • Phenological information helps select species with important ecosystem functions (e.g. early
59 germination and establishment to reduce soil erosion), and helps improve the fine-tuning of post-
60 restoration management regimes (e.g. fire, grazing, mowing intensity/frequency, control of invasive
61 species)

62 • Phenological information (timing of flowering, seed set, nesting, etc.) improves the timing of
63 restoration implementation.

64 • Phenology monitoring provides suitable indicators to assess restoration success.

65

66

67 **Introduction**

68 Phenology is the study of the timing of recurring biological events, the causes of their occurrence
69 with regard to biotic and abiotic forces, and interactions among phases of the same or different
70 species (Lieth 1974; Schwartz 2013). Phenological changes are easily monitored and have marked
71 effects on health, biodiversity, nutrient cycling, forestry, agriculture and the economy (Schwartz
72 2013; Morellato et al. 2016). The study of phenology has gained importance over the past 20 years
73 with the increased concern over climate change (Chambers et al. 2013). Phenology data is
74 increasingly being used to explain and predict various patterns related to other forms of global
75 change (Schwartz 2013), as well as to address applied environmental issues (Morissette et al. 2009;
76 Morellato et al. 2016).

77 While phenology is an interdisciplinary science that has contributed to many disciplines, so far it has
78 not been clearly identified as pertinent for restoration. Morellato et al. (2016) have recently
79 highlighted the importance of phenology for conservation science and management, pointing out the
80 likely implications of phenology for restoration ecology, particularly for seed collection. However,
81 their paper does not explore the various situations in which phenological research can potentially
82 improve the quality of ecological restoration projects. We thus provide here a discussion of how
83 phenological research should be incorporated in ecological restoration. We base this opinion paper
84 on a literature survey in which we examined 149 books, book chapters, or papers relating phenology
85 and restoration (Supporting Information, Appendix S1 and S2, Figure S1, Table S1, S2, S3). Most
86 studies dealt with plant phenology and restoration, likely because plant material is the most
87 important biotic resource used to restore ecosystems. We examine these studies within the
88 framework of the five key steps of restoration projects (Figure 1): 1) establish the reference
89 ecosystem, 2) identify biotic resource needs and sources, and obtain them, 3) implement selected
90 restoration methods and strategies, 4) set up permanent monitoring, and 5) implement adaptive
91 management procedures (Clewett et al. 2005). We lastly discuss how restoration ecology can also
92 contribute to phenological research by providing new insights that will help explore innovative
93 questions on drivers and patterns in phenology.

94

95 **How can phenology improve baseline data on reference ecosystems and biotic resources for**
96 **restoration?**

97 Ecological restoration often requires modification of the physical environment and vegetation
98 manipulation (Whitentan 1999), with the fauna frequently expected to colonize by itself. Although
99 more attention is paid to the animal component nowadays (e.g. taking species interactions into
100 account, or avoiding disturbance to the fauna), the biotic resources used in restoration projects often
101 remain plant material. Despite the fact that animal phenology can be a key factor in improving
102 pollination, seed dispersion and invasive species control (Morellato et al. 2016), and that animals'
103 presence is likely an indicator of restoration success, our review showed that less than 10% of studies
104 refer to animal phenology (and around 15% look at interactions of plants with animals, mainly
105 pollinators or herbivores). The following sections therefore focus more on plant communities and
106 specify the reasons why it is important to collect detailed information on the phenology of plant
107 communities of the reference ecosystem and of the restored site (Figure 1).

108

109 ***Gathering local plant material***

110 Local biotic resources are best for carrying out restoration (Bucharova et al. 2016) and can be
111 obtained by gathering local seeds (e.g. Kiehl et al. 2010). It is obviously necessary to know the
112 phenology of the reference ecosystem plant community in order to adequately plan seed harvest(s).
113 A phenological calendar of the reference plant community or of the target species within the
114 reference plant community was prepared in a number of the reviewed papers and books on various
115 ecosystems (e.g. tallgrass prairies of the USA; Packard et al. 2005). While empirical knowledge of
116 when the majority of fruits are mature is often available in temperate ecosystems, such information
117 is much less common in the tropics or in aseasonal communities. Using phenological information, a
118 fruiting calendar can be created to select seed species, quality, quantity, etc. and to plan effective

119 harvesting. Data on phenology can also help to explain post-restoration differences in species
120 richness between the reference and the restored sites relative to the timing of seed harvests (Kiehl et
121 al. 2006).

122

123 **Optimizing seed production**

124 Prior to seed harvest, management of reference sites can be adapted to optimize seed production,
125 which requires a good understanding of specific management effects on plant phenology. Some of
126 the papers we reviewed investigated fruit production under different management strategies, such
127 as increased soil fertility and decreased toxicity. For example, González Melo & Parrado Rosselli
128 (2010) show that the Andean oak (*Quercus humboldtii*) yields more fruit on soils with a high content
129 of phosphorus and potassium and low soil aluminum. They thus suggest managing the soil to
130 optimize fruit production. Other articles address flowering, fruit production and seed set in relation
131 to disturbance intensity or frequency (fire, grazing, mowing, etc.). Meyer & Schiffman (1999)
132 demonstrate that fire season is a significant factor in grassland restoration, and that the impact of
133 different fire seasons on restoration success is determined by plant phenology patterns and season-
134 specific fire intensities. Wroblewski & Kauffman (2003) indicate that prescribed fire can increase native
135 flower abundances, providing more seeds to be collected for restoration projects. When appropriate,
136 we thus suggest the use of prescribed fires as a management tool to improve fruit production (Figure
137 2, and Supporting Information, Appendix S2 Figure S2).

138

139

140 **Producing local plant material**

141 Gathering wild local plant material is not always an option for restoration: i) because the reference
142 ecosystem may either be protected, ruling out seed harvest, or no longer exist, ii) because the area
143 to be restored may be too big compared to the areas of remaining reference ecosystem, or iii)
144 because it is not very efficient compared to the commercial production of seeds of local
145 provenances. The latter technique is often used, and here too phenology studies can help solve
146 problems of propagation for species yielding low quantities of viable seeds (e.g. *Spartina alterniflora*,
147 saltmarsh cordgrass; Fang et al. 2004). The proportion of each species in commercial seed mixes is
148 determined using various functional types, and early phenology can be a useful criterion to take into
149 account (Carter & Blair 2012). During propagation, the timing of germination, flowering and fruiting
150 of wild plants can change over several generations, because phenological traits are under strong
151 selection. Thus, the plant material might become phenologically ill-adapted (Schröder & Prasse
152 2013). Additionally, once on the restoration sites, cultivated plants can be naturally selected, thus
153 favoring a particular trait, e.g., earlier flowering phenology (Kulpa & Leger 2013). Considering these
154 phenological issues ahead of seeding and out-planting, and even ahead of production, can reveal the
155 importance of using locally adapted plant material (Kiehl et al. 2014) to enhance plant establishment
156 and to increase functional diversity and ecosystem functioning, thus improving restoration.

157

158 **Conserving genetic diversity and local adaptations**

159 Phenological studies can help address the issues related to seed collection by: i) preventing the
160 reduction of genetic diversity of local ecotypes (Holmstrom et al. 2010), and ii) ensuring that seeds
161 are phenotypically suited to their home conditions (Miller et al. 2011). Phenological studies that
162 examine whether flowering times overlap can determine whether native but non-local genotypes
163 introduced on restored sites have the potential to cross-pollinate and to hybridize with surrounding
164 remaining natural genotypes (Holmstrom et al. 2010). Indeed, some introduced genotypes can have
165 advantages over local plants in vegetative and/or sexual reproduction, and can out-compete native
166 genotypes or colonize outside of restoration sites (Holmstrom et al. 2010). Detection of this
167 advantage is particularly important in the case of small and isolated populations (Holmstrom et al.
168 2010). Information on the dates of budbreak, germination, flowering and/or seed set and on flower
169 abundance (Miller et al. 2011) have proven essential to guarantee that using locally adapted seed

170 sources preserves adequate phenological cycles and to ensure the reproductive success of
171 introduced species.

172

173 ***Taking species interactions and ecosystem services into account***

174 Because leaf, flower and fruit phenologies link plants to herbivores, pollinators, frugivores and seed
175 dispersers, studying plant phenology involves taking into account resource availability and
176 interaction networks, encompassing ecosystem and landscape complexity (Hagen et al. 2012). In the
177 context of food webs, phenology helps detect when and in which conditions a particular food
178 resource is available, and can pin-point habitat restoration needs for the species feeding on this
179 particular resource (e.g. Wroblewski & Kauffman 2003). When restoring/reintroducing a population,
180 some knowledge of species phenology (food, competitors, etc.) regarding this restored population is
181 particularly important. As an example, phenology can provide restorationists with a method that
182 selects plant species based on the timing of fruiting. This will enable them to attract potential seed
183 dispersers and provide fruits all year long (Garcia et al. 2014), to match fruit availability with
184 frugivore requirements over time and space (Gosper & Vivian-Smith 2009) and to connect the
185 landscape through resources for both pollinators and seed dispersers (Hagen et al. 2012; Morellato
186 et al. 2016). Phenology thus facilitates the restoration of ecosystem services, such as key food and
187 other non-timber resources (e.g. fruits, leaves, medicinal plants), and can help sustain human
188 population needs (Garibaldi et al. 2013) (see another example in Supporting Information, Appendix
189 S2 Figure S2). Plant phenology on restoration sites should be combined with the phenology of
190 pollinators, seed dispersers or migrating species among others (Schellhorn et al. 2015). This would
191 make it possible to encompass not only most scales, from local communities to ecosystems, focusing
192 on connectivity across the landscape, but also time (e.g. asynchrony on flowering or fruiting time
193 between restored and reference sites may break the temporal connectivity between vegetation
194 patches).

195

196 **How can phenology enhance restoration treatments and management?**

197 ***Optimizing the timing of restoration treatments***

198 Restoration treatments also have to be finely tuned and timed to maximize target species
199 establishment and minimize the harm done to healthy populations of plants or animals remaining in
200 the degraded site to be restored. To achieve this, the phenology of different groups of species (not
201 just plants) needs to be known. Phenological information can be useful to avoid disturbance (e.g.
202 destruction of bird nesting) during the restoration process or to maximize plant establishment from
203 the seed bank. A calendar taking into account the phenology of both animals and plants is often the
204 basis of restoration planning (Jaunatre et al. 2011), although it is rarely clearly stated as phenological
205 information in the papers reviewed.

206

207 ***Dealing with exotic species***

208 In the case of restoration involving removal or control of exotic species, appropriate timing of
209 treatment application requires knowledge of both native and exotic species phenology. Exotics can
210 leaf or bloom during times when natives do not (thus filling a vacant niche), or can flower or
211 germinate earlier than natives (thus benefiting from a priority effect; Wolkovich & Cleland 2011;
212 Figure 1). Restoration treatments should therefore be applied when exotics are vulnerable but
213 natives are not (e.g., fire, grazing, herbicide; Marushia et al. 2010; Ruckman et al. 2012).

214 Phenology studies can also facilitate accurate identification of the risks from non-native species. For
215 example, precise identification of natives and exotics with matching phenology may pin-point species
216 that could then hybridize and induce a loss of both genetic diversity and locally adapted populations
217 (Vilà et al. 2000). Species with matching phenologies can also be in competition for pollinators and
218 dispersers, thereby altering fruit quantity, quality and dispersal, and thus community structure and
219 ecosystem functioning (Vilà et al. 2000; Morellato et al. 2016).

220

221 ***Recovering ecosystem functions***

222 Because of the constant feedback occurring between the abiotic environment and the biota
223 (Temperton et al. 2004), precise information on the phenology of species can allow restorationists to
224 re-introduce species that contribute to the recovery of some ecosystem functions. Native species
225 with spring phenologies can reduce early-season nutrient run-off (Brudvig 2010). Fire can increase
226 flower abundance and extend phenology, which can have a positive effect on bird species foraging
227 activities (Wroblewski & Kauffman 2003) (Figure 2). Therefore, taking phenology into account when
228 planning the timing and intensity of restoration treatments will enhance restoration of ecosystem
229 regulating functions (e.g. nutrient conservation) or supporting functions (e.g. food resources).
230 Moreover, enriching plant communities invaded by exotic species with selected native species of
231 matching phenologies and competitive characteristics can help them out-compete undesired species
232 (Simmons 2005). Finally, phenology is an essential parameter to evaluate restoration treatments and
233 post-restoration management (e.g., Carter & Blair 2012). This should encourage restorationists: i) to
234 focus on ecosystem functions and species composition not only as goals but also as tools to reach
235 restoration objectives (Shackelford et al. 2013); and ii) to incorporate phenology in restoration
236 planning (Figure 1).

237

238 **How can phenology improve restoration monitoring?**

239 Monitoring sites before and after restoration is essential in order to assess the success of restoration
240 projects in achieving pre-defined goals and to improve future restoration practices (Holl & Cairns
241 2002). It is also one of the main aspects that need improvement in restoration projects (Palmer et al.
242 2005). Parameters monitored for restoration depend on the objectives of the project and can be very
243 diverse (Kollmann et al. 2016), ranging from ecosystem functioning to the presence of target species
244 such as plankton (Anneville et al. 2007) or aquatic plants (Cho & Poirrier 2005), reference grassland
245 species (Kiehl et al. 2006), forb species (Wroblewski & Kauffman 2003), trees (Garcia et al. 2014), larval
246 amphibians and predatory macroinvertebrate families (Curtis & Paton 2010), and seabirds (Hall &
247 Kress 2004).

248 The main phenological monitoring techniques are based on seasonal in-the-field species monitoring,
249 but recent studies have used remote sensing to monitor restored ecosystems: Dufour et al. (2013)
250 applied Light Detection And Ranging (LiDAR), radar, and Unmanned Aerial Vehicle (UAV), and van
251 Leeuwen (2008) analyzed a Normalized Difference Vegetation Index (NDVI) from satellite imagery.
252 Repeated photographs taken by digital cameras can also be a cheap and efficient way to monitor
253 species and community changes over time (see Richardson et al. 2009; Alberton et al. 2014), before
254 or after restoration.

255

256 **What can phenology research learn from restoration?**

257 The different phenological studies included in restoration projects were carried out with various
258 restoration improvement aims: identify the best plan monitoring time (Cho & Poirrier 2005), define
259 the right timing for application of restoration treatments (Cho & Poirrier 2005), study the effects of
260 restoration treatments on interactions (Wroblewski & Kauffman, 2003; Anneville et al. 2007; Garcia et
261 al. 2014), provide information on the effectiveness of restoration treatments (Kiehl et al. 2006) and
262 plan management (Curtis & Paton 2010). However, well-established monitoring in restoration
263 ecology can also feed long-term phenological databases on reference ecosystems, target, dominant
264 or rare species, providing many new insights into phenological patterns (Table 1). A wide range of
265 research questions remains to be tackled (Table 1). Can the phenology of native species or invasive
266 species determine their co-occurrence or their ability to colonize and become established in the
267 restored area? Do we observe variations in phenological patterns in plant species/communities that
268 could be related to the modification of edaphic conditions? Can we re-establish interactions or
269 ecosystem services using non-local plants or using local plants according to their phenology? Do
270 some restoration treatments affect plant phenology, and how do these treatments affect plant-
271 animal interactions? As restoration is commonly seen as an acid test of theoretical ecology
272 (Bradshaw 1990), we suggest that restoration can enhance the understanding of phenological
273 patterns within the framework of land-use change.

274
275
276
277
278
279
280
281
282
283
284
285
286
287
288
289
290
291
292
293
294
295
296
297
298
299
300
301
302
303
304
305
306
307
308
309
310
311
312
313
314
315
316
317
318
319
320
321
322
323
324

Conclusion

This paper aimed to increase awareness of the potential of phenological research to improve the quality of ecological restoration projects. While our literature survey demonstrates this potential, we find that phenology is currently mainly applied to assessing biotic resources. Thus, we conclude that phenology remains widely underexplored within restoration projects. Yet phenology has a huge capacity to improve the quality of ecological restoration, and many more applications to restoration remain to be explored.

In order to better understand the role that phenological research can play in restoration, restorationists and land managers should: 1) acknowledge that they are using phenological data, (phenological data is often used empirically without being mentioned in technical reports and articles), and 2) work at incorporating phenology into all stages of restoration projects, when appropriate. Restoration guidelines should promote at least basic, rapidly-performed phenology monitoring tasks, such as regular monitoring of sown, keystone, dominant or rare species on restored sites. The Society for Ecological Restoration International Science & Policy Working Groups should promote the use of phenology in restoration projects in appropriate documents, such as future restoration guidelines (e.g. Shackelford et al. 2013).

Acknowledgements

The authors would like to thank Megan F. King and Marjorie Sweetko for reviewing the English, and the Phenology Lab members, F. Mesléard, T. Dutoit, two reviewers and coordinating editor S. Allison for improving previous versions. This work was supported by: EB - French Embassy / UNESP Rio Claro Chairs 2012 and 2014; STA - post-doctoral fellowships from UNESP PROPe and São Paulo Research Foundation (FAPESP) (grant #2014/12728-1); SLS - post-doctoral fellowship from PVE, CNPq (grant #150404/2016-6); LPCM - São Paulo Research Foundation (FAPESP): grants #2010/52113-5, #2013/50155-0, #2010/51307-0) and Research Productivity Fellowship from CNPq.

References

- Alberton B, Almeida J, Helm R, da S. Torres R, Menzel A, Morellato LPC (2014) Using phenological cameras to track the green up in a cerrado savanna and its on-the-ground validation. *Ecological Informatics* 19:62–70. doi: 10.1016/j.ecoinf.2013.12.011
- Anneville O, Molinero JC, Souissi S, Balvay G, Gerdeaux D (2007) Long-term changes in the copepod community of Lake Geneva. *Journal of Plankton Research* 29:i49–i59.
- Bradshaw AD (1990) Restoration: an acid test for ecology. In: *Restoration Ecology: A Synthetic Approach to Ecological Research*, Cambridge University Press. Cambridge, UK, pp 23–30
- Brudvig LA (2010) Woody encroachment removal from midwestern oak savannas alters understory diversity across space and time. *Restoration Ecology* 18:74–84. doi: 10.1111/j.1526-100X.2008.00431.x
- Bucharova A, Michalski S, Hermann J-M, Heveling K, Durka W, Hölzel N, Kollmann J, Bossdorf O (2016) Genetic differentiation and regional adaptation among seed origins used for grassland restoration: lessons from a multispecies transplant experiment. *Journal of Applied Ecology* n/a-n/a. doi: 10.1111/1365-2664.12645
- Carter DL, Blair JM (2012) Recovery of native plant community characteristics on a chronosequence of restored prairies seeded into pastures in West-central Iowa. *Restoration Ecology* 20:170–179. doi: 10.1111/j.1526-100X.2010.00760.x
- Chambers LE, Altwegg R, Barbraud C, Barnard P, Beaumont LJ, Crawford RJM, Durant JM, Hughes L, Keatley MR, Low M, Morellato PC, Poloczanska ES, Ruoppolo V, Vanstreels RET, Woehler EJ, Wolfaardt AC (2013) Phenological changes in the Southern Hemisphere. *PLoS ONE* 8:e75514. doi: 10.1371/journal.pone.0075514

325 Cho HJ, Poirrier MA (2005) Seasonal growth and reproduction of *Ruppia maritima* L. s.l. in Lake
326 Pontchartrain, Louisiana, USA. *Aquatic Botany* 81:37–49. doi: 10.1016/j.aquabot.2004.10.002

327 Clewell AF, Rieger J, Munro J (2005) Guidelines for developing and managing ecological restoration
328 projects. http://www.ser.org/docs/default-document-library/ser_international_guidelines.pdf.
329 Accessed 5 Feb 2015

330 Curtis AE, Paton PWC (2010) Assessing detection probabilities of larval amphibians and
331 macroinvertebrates in isolated ponds. *Wetlands* 30:901–914. doi: 10.1007/s13157-010-0088-9

332 Dufour S, Bernez I, Betbeder J, Corgne S, Hubert-Moy L, Nabucet J, Rapinel S, Sawtschuk J, Trollé C
333 (2013) Monitoring restored riparian vegetation: how can recent developments in remote
334 sensing sciences help? *Knowledge & Management of Aquatic Ecosystems* 10. doi:
335 10.1051/kmae/2013068

336 Fang X, Subudhi PK, Venuto BC, Harrison SA, Ryan AB (2004) Influence of flowering phenology on
337 seed production in smooth cordgrass (*Spartina alterniflora* Loisel.). *Aquatic Botany* 80:139–
338 151. doi: 10.1016/j.aquabot.2004.07.007

339 Garcia LC, Hobbs RJ, Mães dos Santos FA, Rodrigues RR (2014) Flower and fruit availability along a
340 forest restoration gradient. *Biotropica* 46:114–123. doi: 10.1111/btp.12080

341 Garibaldi LA, Steffan-Dewenter I, Winfree R, Aizen MA, Bommarco R, Cunningham SA, Kremen C,
342 Carvalho LG, Harder LD, Afik O, Bartomeus I, Benjamin F, Boreux V, Cariveau D, Chacoff NP,
343 Dudenhöffer JH, Freitas BM, Ghazoul J, Greenleaf S, Hipólito J, Holzschuh A, Howlett B, Isaacs
344 R, Javorek SK, Kennedy CM, Krewenka KM, Krishnan S, Mandelik Y, Mayfield MM, Motzke I,
345 Munyuli T, Nault BA, Otieno M, Petersen J, Pisanty G, Potts SG, Rader R, Ricketts TH, Rundlöf
346 M, Seymour CL, Schüepp C, Szentgyörgyi H, Taki H, Tschardt T, Vergara CH, Viana BF,
347 Wanger TC, Westphal C, Williams N, Klein AM (2013) Wild pollinators enhance fruit set of
348 crops regardless of honey bee abundance. *Science* 339:1608–1611. doi:
349 10.1126/science.1230200

350 González Melo A, Parrado Rosselli Á (2010) Diferencias en la producción de frutos del roble *Quercus*
351 *humboldtii* Bonpl. en dos bosques andinos de la cordillera oriental colombiana. *Colombia*
352 *Forestal* 13:141–162.

353 Gosper CR, Vivian-Smith G (2009) Approaches to selecting native plant replacements for fleshy-
354 fruited invasive species. *Restoration Ecology* 17:196–204. doi: 10.1111/j.1526-
355 100X.2008.00374.x

356 Hagen M, Kissling WD, Rasmussen C, De Aguiar MAM, Brown LE, Carstensen DW, Alves-Dos-Santos I,
357 Dupont YL, Edwards FK, Genini J, Guimarães PR, Jenkins GB, Jordano P, Kaiser-Bunbury CN,
358 Ledger ME, Maia KP, Marquitti FMD, McLaughlin Ó, Morellato LPC, O’Gorman EJ, Trøjelsgaard
359 K, Tylianakis JM, Vidal MM, Woodward G, Olesen JM (2012) Biodiversity, species interactions
360 and ecological networks in a fragmented world. *Advanced Ecological Research* 46:89–120.

361 Hall CS, Kress SW (2004) Comparison of common tern reproductive performance at four restored
362 colonies along the Maine coast, 1991–2002. *Waterbirds* 27:424–433.

363 Holl KD, Cairns JJ (2002) Monitoring and appraisal. In: *Handbook of Ecological Restoration: Principles*
364 *of Restoration*, Cambridge University Press. Perrow, M.R., Davy A.J., pp 411–432

365 Holmstrom RM, Etterson JR, Schimpf DJ (2010) Dune restoration introduces genetically distinct
366 American beachgrass, *Ammophila breviligulata*, into a threatened local population.
367 *Restoration Ecology* 18:426–437. doi: 10.1111/j.1526-100X.2009.00593.x

368 Jaunatre R, Buisson É, Dutoit T, Dolidon B (2011) Note méthodologique : Exemple de restauration de
369 la plaine de la Crau: l’écologie de la restauration face à la restauration écologique. *Sciences*
370 *Eaux et Territoires* 5:36–39.

371 Kiehl K, Kirmer A, Donath TW, Rasran L, Hölzel N (2010) Species introduction in restoration projects –
372 Evaluation of different techniques for the establishment of semi-natural grasslands in Central
373 and Northwestern Europe. *Basic & Applied Ecology* 11:285–299. doi:
374 10.1016/j.baae.2009.12.004

375 Kiehl K, Kirmer A, Shaw N, Tischew S (2014) *Guidelines for Native Seed Production and Grassland*
376 *Restoration*. Cambridge Scholars Publishing, Newcastle upon Tyne

377 Kiehl K, Thormann A, Pfadenhauer J (2006) Evaluation of initial restoration measures during the
378 restoration of calcareous grasslands on former arable fields. *Restoration Ecology* 14:148–156.
379 doi: 10.1111/j.1526-100X.2006.00115.x

380 Kollmann J, Meyer ST, Bateman R, Conradi T, Gossner MM, de Souza Mendonça Junior M, Fernandes
381 GW, Hermann JM, Koch C, Müller SC, Oki Y, Overbeck GE, Paterno GB, Rosenfield MF, Toma
382 TSP, Weisser WW (2016) Integrating ecosystem functions into restoration ecology – recent
383 advances and future directions. *Restoration Ecology*. doi: 10.1111/rec.12422

384 Kulpa SM, Leger EA (2013) Strong natural selection during plant restoration favors an unexpected
385 suite of plant traits. *Evolutionary Applications* 6:510–523. doi: 10.1111/eva.12038

386 Lieth H (1974) *Phenology and Seasonality Modeling*. Springer-Verlag, New York

387 Marushia RG, Cadotte MW, Holt JS (2010) Phenology as a basis for management of exotic annual
388 plants in desert invasions. *Journal of Applied Ecology* 47:1290–1299. doi: 10.1111/j.1365-
389 2664.2010.01881.x

390 Meyer MS, Schiffman PM (1999) Fire season and mulch reduction in a California grassland: a
391 comparison of restoration strategies. *Madroño* 46:25-37.
392 <http://www.jstor.org/stable/41425292>

393 Miller SA, Bartow A, Gisler M, Ward K, Young AS, Kaye TN (2011) Can an ecoregion serve as a seed
394 transfer zone? Evidence from a common garden study with five native species. *Restoration*
395 *Ecology* 19:268–276. doi: 10.1111/j.1526-100X.2010.00702.x

396 Morellato LPC, Alberton B, Alvarado ST, Borges B, Buisson E, Camargo MGG, Cancian LF, Carstensen
397 DW, Escobar DFE, Leite PTP, Mendoza I, Rocha NMWB, Soares NC, Silva TSF, Staggemeier VG,
398 Streher AS, Vargas BC, Peres CA (2016) Linking plant phenology to conservation biology.
399 *Biological Conservation* 195:60–72. doi: 10.1016/j.biocon.2015.12.033

400 Morisette JT, Richardson AD, Knapp AK, Fisher JL, Graham EA, Abatzoglou J, Wilson BE, Breshears DD,
401 Henebry GM, Hanes JM, Liang L (2009) Tracking the rhythm of the seasons in the face of global
402 change: phenological research in the 21st century. *Frontiers in Ecology and the Environment*
403 7:253–260. doi: 10.1890/070217

404 Packard S, Mutel CF, Jordan WR (2005) *The Tallgrass Restoration Handbook: For Prairies, Savannas,*
405 *and Woodlands, Édition : 2nd New edition*. Island Press, Washington, DC

406 Palmer MA, Bernhardt ES, Allan JD, Lake PS, Alexander G, Brooks S, Carr J, Clayton S, Dahm CN,
407 Follstad Shah J, Galat DL, Loss SG, Goodwin P, Hart DD, Hassett B, Jenkinson R, Kondolf GM,
408 Lave R, Meyer JL, O'Donnell TK, Pagano L, Sudduth E (2005) Standards for ecologically
409 successful river restoration. *Journal of Applied Ecology* 42:208–217. doi: 10.1111/j.1365-
410 2664.2005.01004.x

411 Richardson AD, Braswell BH, Hollinger DY, Jenkins JP, Ollinger SV (2009) Near-surface remote sensing
412 of spatial and temporal variation in canopy phenology. *Ecological Applications* 19:1417–1428.
413 doi: 10.1890/08-2022.1

414 Ruckman EM, Schwinning S, Lyons KG (2012) Effects of phenology at burn time on post-fire recovery
415 in an invasive C4 grass. *Restoration Ecology* 20:756–763. doi: 10.1111/j.1526-
416 100X.2011.00830.x

417 Schellhorn NA, Gagic V, Bommarco R (2015) Time will tell: resource continuity bolsters ecosystem
418 services. *Trends in Ecology and Evolution* 30:524–530. doi: [10.1016/j.tree.2015.06.007](https://doi.org/10.1016/j.tree.2015.06.007)

419 Schröder R, Prasse R (2013) From nursery into nature: A study on performance of cultivated varieties
420 of native plants used in re-vegetation, their wild relatives and evolving wild × cultivar hybrids.
421 *Ecological Engineering* 60:428–437. doi: 10.1016/j.ecoleng.2013.09.036

422 Schwartz MD (2013) *Phenology: An Integrative Environmental Science, Édition : 2nd ed.* 2013.
423 Springer, Dordrecht

424 Shackelford N, Hobbs RJ, Burgar JM, Erickson TE, Fontaine JB, Laliberté E, Ramalho CE, Perring MP,
425 Standish RJ (2013) Primed for change: developing ecological restoration for the 21st century.
426 *Restoration Ecology* 21:297–304. doi: 10.1111/rec.12012

- 427 Simmons MT (2005) Bullying the bullies: the selective control of an exotic, invasive annual (*Rapistrum*
428 *rugosum*) by oversowing with a competitive native species (*Gaillardia pulchella*). *Restoration*
429 *Ecology* 13:609–615. doi: 10.1111/j.1526-100X.2005.00078.x
- 430 Temperton VM, Hobbs RJ, Nuttle T, Halle S (2004) *Assembly Rules and Restoration Ecology: Bridging*
431 *the Gap Between Theory and Practice*. Island Press
- 432 van Leeuwen V (2008) Monitoring the effects of forest restoration treatments on post-fire vegetation
433 recovery with MODIS multitemporal data. *Sensors* 8:2017–2042. doi: 10.3390/s8032017
- 434 Vilà M, Weber E, Antonio CMD (2000) Conservation implications of invasion by plant hybridization.
435 *Biological Invasions* 2:207–217. doi: 10.1023/A:1010003603310
- 436 Whitenant SG (1999) *Repairing Damaged Wildlands: a Process-Oriented, Landscape-Scale Approach*.
437 Cambridge University Press.
- 438 Wolkovich EM, Cleland EE (2011) The phenology of plant invasions: a community ecology
439 perspective. *Frontiers in Ecology and the Environment* 9:287–294. doi: 10.1890/100033
- 440 Wroblewski DW, Kauffman JB (2003) Initial effects of prescribed fire on morphology, abundance, and
441 phenology of forbs in big sagebrush communities in southeastern Oregon. *Restoration Ecology*
442 11:82–90. doi: 10.1046/j.1526-100X.2003.00084.x

443
444
445
446

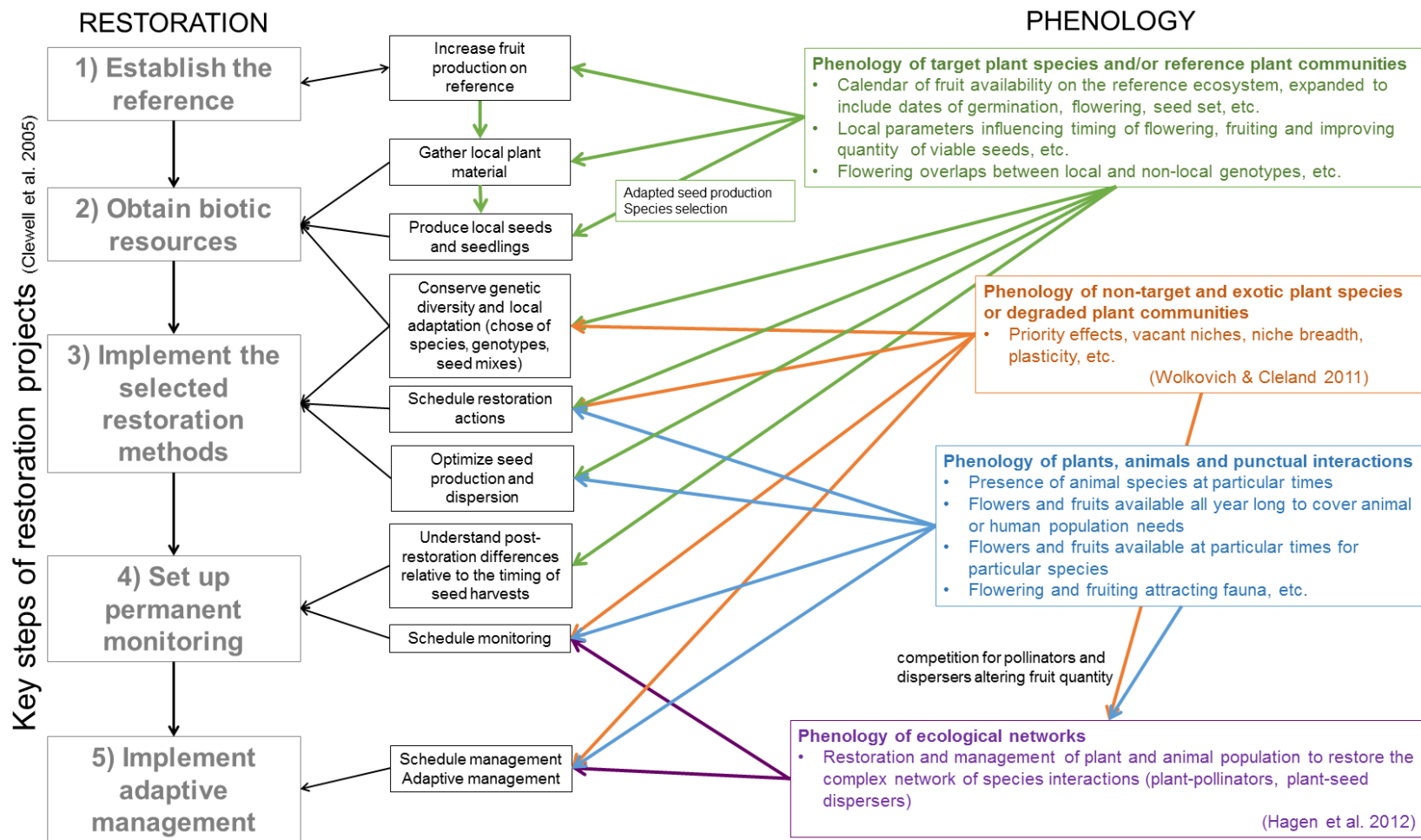
Table 1. Research questions and items that can be tackled on phenology (right hand side) within the context of restoration projects. We organized them according to the five major key steps of restoration projects (Clewell et al. 2005; left hand side).

Key steps of restoration projects	Phenology research questions
1) Establish the reference	<p><i>Phenological data collected to set up restoration projects can generate a good database useful for phenological studies at broad scales. Data can be collected both on the reference ecosystem (e.g., calendar for seed collection) and on the species that established after disturbance on the area to be restored.</i></p> <ul style="list-style-type: none"> → Can phenology help us to understand the occurrence of species and/or their ability to colonize and establish in degraded areas? → Do we observe changes in the phenology of species occurring in restored/degraded areas, in comparison to the phenology observed in pristine areas (phenological differences linked to different environmental conditions, such as microclimate or soil conditions?)
2) Obtain biotic resources	<p><i>Phenological data collected to improve seed collection, to produce seedlings and to better select species, and results of restoration projects using local and non-local plant species, can bring new insight on local phenological patterns.</i></p> <ul style="list-style-type: none"> → Are there advantages in using non-local vs. local plants depending on their phenology? → Are there phenological differences between invasive species and native species or between commercially produced populations and local populations on restored areas? This can, for example, bring new insight on invasive species success.
3) Implement the selected restoration methods	<p><i>Phenological data collected on restored areas and on the species established after restoration. To explore particular questions on the effects of soils or succession on phenology, one can use restored areas instead of having to build specific large-scale protocols.</i></p> <ul style="list-style-type: none"> → Does the restoration treatment (nutrient application, mowing, fire, etc.) affect plant phenology? This should help to understand the impact of nutrient increase on plant phenology. Does mowing applied to restore plant communities modify plant phenology? How does this affect plant-animal interactions? → How do restoration actions influence plant phenology and plant-animal interactions, such as pollination and seed dispersal? → Do the control of invasive species as a treatment to restore degraded areas impact the phenology of invasive species (e.g., fruit production) and/or of native species (e.g., changes of quantity of pollinators might alter phenology or seed

	production of native species transplanted/translocated in degraded areas)
4) Set up permanent monitoring	<p><i>Phenological surveys might be one ecosystem variable that can be used in a restoration evaluation, and phenological data collected during restoration monitoring may generate a good database and long-term data sets useful for phenological studies.</i></p> <ul style="list-style-type: none"> → Monitoring the restored communities should be carried out along with monitoring reference communities which serves as controls; long-term data sets can thus be collected on reference areas and contribute to answering questions such as: how is climate change influencing plant phenology in both restored and pristine areas? → With phenological data on the restored area: How does plant community phenology change along succession? Does restoring plant communities lead to the recovery of plant-animal interactions? → Assessment of the phenology of some transplanted species can improve the global understanding of such species → New techniques of phenology monitoring can be applied to ecological restoration (i.e., monitoring restored communities) and bring some feedback on these techniques as well as the plant responses over time. → Monitoring phenology of restored communities improves our understanding of the ecology of the pristine communities including the plant-animal interactions and their importance to the structure and resilience of plant and animal communities.
5) Implement adaptive management	<p><i>Adaptive management on restored sites may generate data coupled with particular management regime.</i></p> <ul style="list-style-type: none"> → How does plant phenology change with changes in management type or regime? → How do finely timed plant-animal interactions change with restoration? → Can restored phenological patterns help re-establish interactions or ecosystem services and with what management regime?

448 Figure 1. Conceptual framework showing where phenology can contribute to restoration. Numbers 1 to 5 are five major key steps of restoration projects
 449 (Clewell et al. 2005). Phenological information that may be collected for restoration projects are found in boxes on the right hand side of the figure. Arrows
 450 show how specific phenological information can contribute to specific restoration steps.

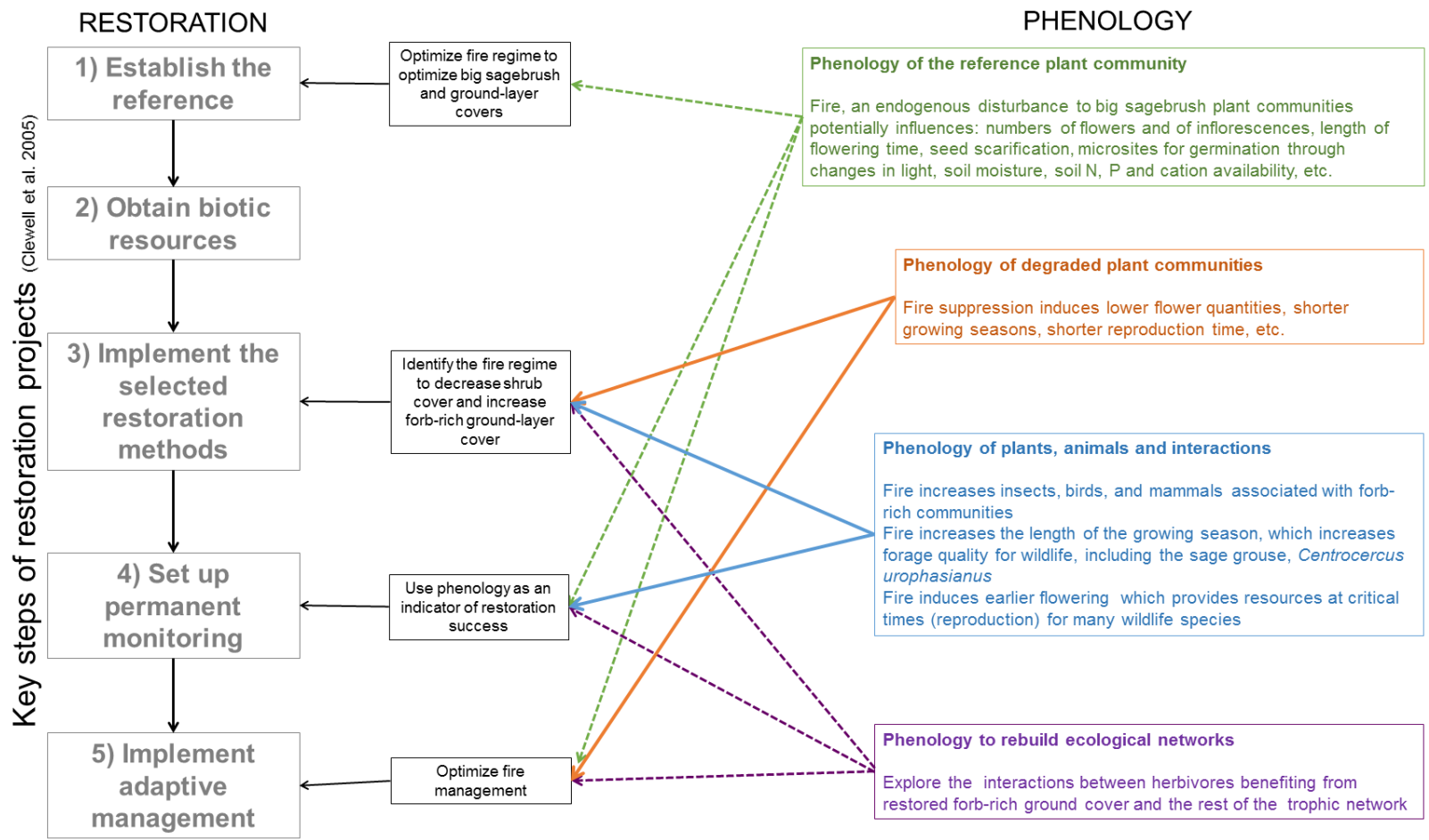
451



452

453

454 Figure 2. Example of the application of phenology to restoration based on a study by Wroblewski & Kauffman (2003) carried out with the following reference
 455 ecosystem: open big sagebrush (*Artemisia tridentata*) plant community with a rich ground-layer of forbs and grasses (Great Basin and Intermountain
 456 regions of the US Pacific Northwest). Solid lines represent the phenological information gathered in this study. Dotted lines represent either information
 457 gathered in other studies (cited in Wroblewski & Kauffman 2003) or future phenological studies that would help subsequent restoration steps.
 458



Appendix S1–“Literature survey and reviewing process”

In February 2014, we used Google Books and the words “phenology” or “phenological” to perform a systematic search of forty-two books dealing with restoration (Table S1). We also performed a systematic survey of articles dealing with phenology in the context of restoration. We searched for articles in: 1) *Restoration Ecology*, the main journal publishing research on restoration and allowing the exchange of ideas among the many disciplines involved in the process of ecological restoration, using the term “phenolog*” in the full text, from 1993 to February 2014; and 2) the large database available in *Web of Science*, using the terms “restoration” AND “phenolog*” in the search topic, from 1985 to February 2014.

After retrieving 404 chapters and papers, we removed 255 that only mentioned phenology without giving any details, or which mentioned phenology in contexts that were not relevant to restoration, or which were simply related to plant survival and growth after restoration without further insights into the role of phenology. We then reviewed the 149 relevant chapters and papers, and synthesized them by collecting data on the contexts in which the keywords “phenolog*” and “restor*” were mentioned. To do so, we classified them into categories according to the context in which the keywords were used. These categories were not pre-established: a new category was created every time a paper introduced the keywords in a new context. We ended up with nine categories as shown in Table S2. Each paper could be classified in several categories. The results below use the nine categories identified while reading the papers.

Appendix S1 - Table S1. Title, year of publication and authors or editors of the 42 books dealing with restoration that were searched for the word “phenology” or “phenological”. Dark grey lines correspond to books (9) that did not mention the word “phenology” or “phenological”, light grey lines to books (7) that mentioned either one of them but in a context that is not directly relevant to restoration and white lines to books (26) that mentioned one of these two words in a context relevant to restoration (see Table S3 for details).

Authors/Editors	Year	Title
Allison S.K.	2012	Ecological Restoration and Environmental Change: Renewing Damaged Ecosystems
Apfelbaum S.I. & Haney A.W.	2010	Restoring Ecological Health to your Land
Aronson J., Milton S.J. & Blignaut J.N. (eds)	2007	Restoring Natural Capital: Science, Business, and Practice
Aronson J., Santos Pereira J. & Pausas J.G.(eds)	2009	Cork Oak Woodlands on the Edge: Ecology, Adaptive Management, and Restoration
Bainbridge D.A.	2007	A Guide for Desert and Dryland Restoration
Bowles M.L. & Whelan C.J. (eds)	1996	Restoration of Endangered Species: Conceptual Issues, Planning and Implementation
Brierley G.J. & Fryirs K.A. (eds)	2008	River Futures: an Integrative Scientific Approach to River Repair
Clewell A.F. & Aronson J.	2007	Ecological Restoration - Principles, Values, and Structure of an Emerging Profession
Comin F.A. (ed).	2010	Ecological Restoration - a Global Challenge
Court F.	2012	Pioneers of Ecological Restoration: the People and Legacy of the University of Wisconsin Arboretum
Ewen J.G., Armstrong D.P., Parker K.A. & Seddon P.J. (eds)	2012	Reintroduction Biology: Integrating Science and Management
Falk D.A., Millar C.I. & Olwell M.(eds)	1996	Restoring Diversity: Strategies for Reintroduction of Endangered Plants
Falk D.A., Palmer M.A. & Zedler J.B. (eds)	2006	Foundations of Restoration Ecology
Friederici P. (ed)	2003	Ecological Restoration of Southwestern Ponderosa Pine Forests
Halldórsson G., Aradóttir A.L., Fosaa A.M., Hagen D., Nilsson C., Raulund-Rasmussen K., Brekke Skringdo A., Svavarsdóttir K. & Tolvanen A.	2012	Restoration of Damaged Ecosystems in the Nordic Countries
Hobbs R.J. & Cramer V.A. (eds)	2007	Old Fields: Dynamics and Restoration of Abandoned Farmland

Authors/Editors	Year	Title
Hobbs R.J., Higgs E.S. & Hall C.M. (eds)	2013	Novel Ecosystems: Intervening in the New Ecological World Order
Hobbs R.J. & Sudin K.N. (eds)	2008	New models for Ecosystem Dynamics and Restoration
Jordan III W.R., Gilpin M.E. & Aber J.D. (eds)	1990	Restoration Ecology - a Synthetic Approach to Ecological Research
Lamb D.	2010	Regreening the Bare Hills: Tropical Forest Restoration in the Asia-Pacific Region
L'Huillier L., Jaffré T., Wulff A. (eds)	2010	Mines et Environnement en Nouvelle-Calédonie : les Milieux sur Substrats Ultramafiques et leur Restauration
Mansourian S., Vallauri D. & Dudley N. (eds)	2005	Forest Restoration in Landscapes - Beyond Planting Trees
Martínez L.M., Gallego-Fernández J.B. & Hesp P.A. (eds)	2013	Restoration of Coastal Dunes
Morrison M.L.	2009	Restoring Wildlife: Ecological Concepts and Practical Applications
Morrison M.L.	2002	Wildlife Restoration: Techniques for Habitat Analysis and Animal Monitoring
Naveh Z.	2007	Transdisciplinary Challenges in Landscape Ecology and Restoration Ecology
Newton A.C. & Tejedor N. (eds)	2011	Principles and Practice of Forest Landscape Restoration Case Studies from the Drylands of Latin America
Nordstrom K.F.	2008	Beach and Dune Restoration
Packard S. & Mutel C.F. (eds)	2005	The Tallgrass Restoration Handbook, for Prairies, Savannas and Woodlands
Perrow M.R. & Davy A.J. (eds)	2008	Handbook of Ecological Restoration: Principles of Restoration
Peters M. & Clarkson B. (eds)	2010	Wetland restoration : a Handbook for New Zealand Freshwater Systems
Ribeiro Rodrigues R., Venâncio Martins S. & Gandolfi S. (eds)	2007	High Diversity Forest Restoration in Degraded Areas: Methods and Projects in Brazil
Rietbergen-McCracken J., Maginnis S. & Sarre A. (eds)	2012	The Forest Landscape Restoration Handbook
Roman C.T. & Burdick D.M. (eds)	2012	Tidal Marsh Restoration: a Synthesis of Science and Management
Roni P. & Beechie T. (eds)	2013	Stream and Watershed Restoration: a Guide to Restoring Riverine Processes and Habitats
Roundy B.A., Durant McArthur E., Hayley J.S. & Mann D.K. (eds)	1996	Wild Land Shrub and Arid Land Restoration Symposium: Proceedings
Soorae P.S. (ed)	2011	Global Reintroduction Perspective: 2011
Stanturf J.A., Madsen P. & Lamb D. (eds)	2012	A Goal-Oriented Approach to Forest

Authors/Editors	Year	Title
		Landscape Restoration
Temperton V.M., Hobbs R.J., Nuttle T. & Halle S. (eds)	2004	Assembly Rules and Restoration Ecology - Bridging the Gap Between Theory and Practice
van Andel J. & Aronson J. (eds)	2012	Restoration Ecology: the New Frontier
Vitt D. & Bhatti J. (eds)	2013	Restoration and Reclamation of Boreal Ecosystems Attaining Sustainable Development
Walker L. & Del Moral R.	2003	Primary Succession and Ecosystem Rehabilitation

Appendix S1 - Table S2. Categories adopted to classify the studies used in the literature review according to the different contexts in which phenology and restoration were addressed in the studies.

Category	Definition based on papers surveyed
exotic species	potential negative interactions between target and exotic species phenology
species interaction	potential interactions between target and other species phenology
functions/traits	the restoration of particular ecosystem functions, plant functional or life-traits related to phenology
genetic provenance	differences in the phenology of target species depending on the seed provenance
germination	germination phenology
management	phenology within the context of applying a particular type of management on a restored site
monitoring	monitoring of reproductive phenology on the restored ecosystem (post-restoration monitoring)
seed harvest, production and mixes	collection of phenological data on the target species of their restoration project to improve seed collection, seed mixes or studied difference in the phenology of cultivated vs. wild species (pre-restoration monitoring)
lack of knowledge	there is not enough information on the phenology of the target species of their restoration project

Appendix S2–“Results of the survey”

Out of the 42 books analyzed, nine did not mention either the word “phenology” or “phenological” (Figure S1). Of the 33 other books (including 627 chapters), 49 books and book chapters mentioned phenolog* at least once: 21 did so in a context that was not relevant to this study (e.g. in the context of climate change), and only 28 mentioned either “phenology” or “phenological” in a context relevant to restoration. Most of the mentions concerned “seed harvest, production and mixes” (34.5%) and “lack of knowledge” (24.1%). The other categories together totaled 41.4%: exotic species (6.9%), functions/traits (0%), genetic provenance (10.3%), germination (0%), management (10.3%), monitoring (6.9%) and species interactions (6.9%) (Table S3). We did not expect to find so many mentions of a lack of phenological knowledge that might otherwise be useful for restoration. This category is particularly well represented in book chapters, probably because it is easier to mention a flaw in a book on a particular theme or ecosystem than in articles. The “seed harvest, production and mixes” category is also well represented because many of the books were concerned with a particular ecosystem, such as Southwestern ponderosa pine forests, tallgrass prairies, dry forests in Chiapas, Mexico or floodplain forests in Europe, etc., where a lot of precise information is available (Table S3).

In *Restoration Ecology* (which published 1644 papers up to February 2014), 183 papers contained the term “phenolog*”, 163 in a context not relevant to this study or simply related to plant survival and growth (Figure S1). Twenty papers mentioned the term “phenolog*” in a context directly related to restoration projects (1.22% of the articles published in *Restoration Ecology*; Table S3). They were well distributed among the nine categories (Table S3): seven papers (22.6%) discussed phenology within the context of “species interactions”, five (16.1%) within the context of “genetic provenance”, another five (16.1%) on “monitoring”, four (12.9%) within the context of “exotic species” and four (12.9%) on “seed harvest, production and mixes”. Other categories had few papers (management and functions/traits: two papers each (6.5%), and germination and lack of knowledge: one paper each (3.2%)).

The *Web of Science* database (8695 papers published on restoration) yielded 172 papers containing the terms “restoration” AND “phenolog*” in the topic (Figure S1). Out of those 172 papers, 71 mentioned “phenolog*” in a context which was not relevant to this study. Of the 101 papers analyzed (1.16% of the articles concerning restoration in *Web of Science*), the majority were published after 2004, most from 2009 onwards, yielding from 15 to 20 papers per year. The most common contexts in which the term phenology was cited were (Table S3): “seed harvest, production and mixes” (25 papers, 18.9%), “species interaction” (24 papers, 18.2%), “genetic provenance” (21 papers, 15.9%), “management” (17 papers, 12.9%) and “germination” (16 papers, 12.1%). Other categories had fewer papers (monitoring: 15 papers (11.4%), exotic species: 11 papers (8.3%), functions/traits: 3 papers (2.3%), and there was no paper on lack of knowledge.

Most of the 149 books, book chapters and papers selected dealt with plant phenology, although 20 reported data on animal phenology (insects, crustaceans, amphibians, fish, birds, lemurs). Our study is far from exhaustive, as not all the papers that deal with restoration and phenology were found in the databases. This is partly because not all authors mentioned i) the word phenology even though they actually studied some phenologically-driven patterns, or ii) the word restoration even when the study could be relevant to restoration (e.g. invasive species control or managed relocation). Nevertheless, the results of our literature survey allowed us to identify recurrent themes and to build a framework for links between phenology and restoration based on five key steps of restoration projects (Figure 1): 1) establish the reference ecosystem, 2) identify biotic resource needs and sources, and obtain them, 3) implement selected restoration methods and strategies, 4) set up permanent monitoring, and 5) implement adaptive management procedures (Clewell et al. 2005).

Literature cited for Appendix S2

Clewell AF, Rieger J, Munro J (2005) Guidelines for developing and managing ecological restoration projects. http://www.ser.org/docs/default-document-library/ser_international_guidelines.pdf. Accessed 13 Oct 2016

Appendix S2 - Table S3

List of the 149 relevant chapters or papers selected for this study. We identified 28 book chapters, 20 articles in the journal *Restoration Ecology*, and 101 articles on the Web of Science (out of 404 surveyed) which studied both phenology and restoration and which were relevant to restoration according to at least one of the nine categories of application: exotic species; functions/traits; genetic provenance; germination; management; monitoring; seed harvest, production and mixes; species interactions; and lack of knowledge (Table S2). Source: DB = Database, BC = book or book chapter, RE = *Restoration Ecology* and WS = Web of Science.

Source	Title of paper of chapter	Date	Authors	Journal / Book	Categories									
					exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge	
BC		2012	Van Andel J, Aronson J	Restoration Ecology: the New Frontier					x					
BC	Prairies	1990	Kline VM, Howell EA	Restoration Ecology - a Synthetic Approach to Ecological Research Jordan III WR, Gilpin ME, Aber JD (eds)										x
BC	Restoration, revegetation, and the importance of genetic and evolutionary perspectives	1996	Linhart YB	Wild Land Shrub and Arid Land Restoration Symposium: Proceedings Roundy BA, Durant McArthur E, Hayley JS, Mann DK (eds)			x							

Source	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
					exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
BC	Texas snowbells (<i>Styrax texana</i>) reintroduction	1996	McDonald CB	Restoring Diversity: Strategies for Reintroduction of Endangered Plants Falk DA, Olwell M, Millar CI (eds)						x			
BC	Exotic invasive plants	2003	Sieg CH, Phillips BG, Moser LP	Ecological Restoration of Southwestern Ponderosa Pine Forests Friederici P (ed)	x								
BC	Understory vegetation	2003	Korb JE, Springer JD	Ecological Restoration of Southwestern Ponderosa Pine Forests Friederici P (ed)							x		
BC	Stimulating natural regeneration	2005	Holz S, Placci G	Forest restoration in Landscapes - Beyond planting trees Mansourian S, Vallauri D, Dudley N (eds)									x
BC	Obtaining and processing seeds	2005	Apfelbaum SI, Bader BJ, Faessler F, Mahler D	The Tallgrass Restoration Handbook, for Prairies, Savannas and Woodlands S Packard (ed)							x		

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
BC		Population and ecological genetics in restoration ecology	2006	Falk DA, Richard CM, Montalvo AM, Knapp EE	Foundations of Restoration Ecology Falk DA, Palmer MA, Zedler JB			x						
BC		Using ecological theory to manage or restore ecosystems affected by invasive plant species	2006	D'Antonio CM, Chambers JC	Foundations of Restoration Ecology Falk DA, Palmer MA, Zedler JB								x	
BC		Project planning and evaluation	2007	Clewell AF, Aronson J	Ecological Restoration - Principles, Values, and Structure of an Emerging Profession			x						
BC			2007	Ribeiro Rodrigues R, Venâncio Martins S	High Diversity Forest Restoration in Degraded Areas: Methods and Projects in Brazil					x				x
BC		Return of natural, social, and financial capital to the hole left by mining	2007	van Eeden JD, Lubke RA, Haarhoff P	Restoring Natural Capital: Science, Business, and Practice Aronson J, Milton SJ, Blignaut JN (eds)									x
BC		Monitoring and appraisal	2008	Holl K, Cairns Jjr	Handbook of Ecological Restoration: Principles of Restoration						x			

Source	Title of paper of chapter	Date	Authors	Journal / Book	Categories									
					exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge	
				Perrow MR, Davy AJ (eds)										
BC		2010	Apfelbaum SI, Haney AW	Restoring Ecological Health to your Land							x			
BC		2010	L'Huillier L, Jaffré T, Wulff A	Mines et Environnement en Nouvelle-Calédonie : les Milieux sur Substrats Ultramafiques et leur Restauration.							x			
BC		2010	Lamb D	Regreening the Bare Hills: Tropical Forest Restoration in the Asia-Pacific Region					x					
BC	Tropical dry forest restoration in Chiapas, Mexico and basic knowledge for native tree species: phenology, seed germination and seedling growth	2011	Becerra Vazquez AG, Ramierz-Marcial N, Holz SC	Principles and Practice of Forest Landscape Restoration Case Studies from the Drylands of Latin America Newton AC, Tejedor N (eds)							x			

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories										
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge		
BC		Experimental analysis of dryland forest restoration techniques	2011	Willamns-Linera G, Alvarez-Aquino C, Suarez A, Blundo C, Smith-Ramirez C, Echeverria C, Cruz-Cruz E, Bolados G, Armesto JJ, Heinemann K, Malizia L, Becarra P, del Castillo RF, Urrutia R	Principles and Practice of Forest Landscape Restoration Case Studies from the Drylands of Latin America Newton AC, Tejedor N (eds)										x	
BC		Synthesis: principles and practice of forest landscape restoration	2011	Newton AC	Principles and Practice of Forest Landscape Restoration Case Studies from the Drylands of Latin America Newton AC, Tejedor N (eds)											x
BC		Integrating scientific research with community needs to restore a forest landscape in Northern Thailand: A case study of Ban Mae Sa Mai	2012	Elliot S, Kuaraksa C, Tunjai P, Toktang T, Boonsai K, Sangkum S, Suwannaratana S, Blakesley D	A Goal-Oriented Approach to Forest Landscape Restoration Stanturf J, Madsen P, Lamb D (eds)							x				

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
BC		Restoration of deforested and degraded areas in Africa	2012	Blay D	A Goal-Oriented Approach to Forest Landscape Restoration Stanturf J, Madsen P, Lamb D (eds)							x		
BC		Restoring floodplain forests in Europe	2012	Hughes FMR, Gonzales del Tanago M, Mountford JO	A Goal-Oriented Approach to Forest Landscape Restoration Stanturf J, Madsen P, Lamb D (eds)							x		
BC		Vegetation response to tidal restoration	2012	Smith SM, Warren RS	Tidal Marsh Restoration: A Synthesis of Science and Management Roman CT, Burdick DM (eds)	x								
BC		Selecting suitable habitats for reintroductions: variation, change and the role of species distribution modelling	2012	Osborne PE, Seddon PJ	Reintroduction Biology: Integrating Science and Management Ewen JG, Armstrong DP, Parker KA, Seddon PJ (eds)								x	
BC		Open-cast mining reclamation	2005	Nicolau Ibarra JM, Moreno de las Heras M	Forest restoration in Landscapes - Beyond Planting Trees Mansourian S, Vallauri							x		

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
					D, Dudley N (eds)									
BC		Restoring tropical moist broad-leaf forests	2005	Lamb D	Forest restoration in Landscapes - Beyond Planting Trees Mansourian S, Vallauri D, Dudley N (eds)									x
BC		Selecting tree species for plantation	2005	Montagnini F	Forest restoration in Landscapes - Beyond Planting Trees Mansourian S, Vallauri D, Dudley N (eds)						x			
RE		Burning and grazing management in a California grassland: growth, mortality, and recruitment of <i>Nassella pulchra</i>	2003	Dyer AR	Restoration Ecology	x							x	
RE		Bullying the bullies: the selective control of an exotic, invasive annual (<i>Rapistrum rugosum</i>) by oversowing with a competitive native	2005	Simmons, MT	Restoration Ecology	x						x	x	

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
RE		Approaches to selecting native plant replacements for fleshy-fruited invasive species	2009	Gosper CR, Vivian-Smith G	Restoration Ecology								x	
RE		Recovery of native plant community characteristics on a chronosequence of restored prairies seeded into pastures in west-central Iowa	2012	Carter DL, Blair JM	Restoration Ecology				x		x	x		
RE		Evaluation of initial restoration measures during the restoration of calcareous grasslands on former arable fields	2006	Kiehl K, Thormann A, Pfadenhauer J	Restoration Ecology						x	x		
RE		Intra- and interannual vegetation change: implications for long-term research	2008	Korb JE, Fulé PZ	Restoration Ecology						x			
RE		Initial effects of prescribed fire on morphology, abundance, and phenology of forbs in big sagebrush	2003	Wroblewski DW, Kauffmann JB	Restoration Ecology					x	x		x	

Source					Categories								
DB	Title of paper of chapter	Date	Authors	Journal / Book	exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
	communities in southeastern Oregon												
RE	Effects of phenology at burn time on post-fire recovery in an invasive C4 grass	2012	Ruckman EM, Schwinning S, Lyons KG	Restoration Ecology	x				x				
RE	Strengthening invasion filters to reassemble native plant communities: soil resources and phenological overlap	2013	Cleland EE, Larios L, Suding KN	Restoration Ecology	x							x	
RE	Genecology of <i>Holodiscus discolor</i> (Rosaceae) in the Pacific Northwest, U.S.A.	2010	Horning ME, McGovern TR, Darris DC, Mandel NL	Restoration Ecology			x						
RE	Can an ecoregion serve as a seed transfer zone? Evidence from a common garden study with five native species	2011	Miller, SA, Bartow A, Gisler M, Ward K, Kaye TN	Restoration Ecology			x						

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
RE		Genetic variation for adaptive traits in bottlebrush squirreltail in the northern intermountain west, United States	2011	Parsons MC, Jones TA, Monaco TA	Restoration Ecology			x						
RE		Flowering phenology and genetic similarity among local and recently introduced populations of <i>Andropogon gerardii</i> in Ohio	2005	Selbo SM, Snow AA	Restoration Ecology			x						
RE		Effects of established perennial grasses on introduction of native forbs in California	2001	Brown CS, Bugg RL	Restoration Ecology		x							x
RE		Woody encroachment removal from midwestern oak savannas alters understory diversity across space and time	2010	Brudvig LA	Restoration Ecology		x							

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
RE		Restoration of magnesian limestone grassland: optimizing the Time for seed collection by vacuum harvesting	2004	Riley JD, Craft IW, Rimmer DL, Smith RS	Restoration Ecology							x		
RE		Vegetation colonization in a restoring tidal marsh: A remote sensing approach	2008	Tuxen KA, Schile LM, Kelly M, Siegel SW	Restoration Ecology						x			
WS		Considering local adaptation in issues of lepidopteran conservation - a review and recommendations	2011	Aardema ML, Scriber JM, Hellmann JJ	American Midland Naturalist								x	
WS		Reproductive phenology in a riparian rainforest in the south of Santa Catarina state, Brazil	2013	Cascaes MF, Citadini-Zanette V, Harter-Marques B	Anais da Academia Brasileira de Ciencias							x		
WS		Genetic variation between <i>Lupinus elegans</i> Kunth provenances, altitudal seed zoning and assisted migration	2012	Soto-Correa JC, Saenz-Romero C, Lindig-Cisneros R, Sanchez-Vargas N, Cruz-de-Leon J	Agrociencia			x						
WS		Genecology and seed zones for tapertip onion	2013	Johnson RC, Hellier BC, Vance-Borland KW	Botany-Botanique			x						

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
		in the US Great Basin												
WS		Influence of flowering phenology on seed production in smooth cordgrass (<i>Spartina alterniflora</i> Loisel.)	2004	Fang XB, Subudhi PK, Venuto BC, Harrison SA, Ryan AB	Aquatic Botany							x		
WS		Seeding ecological restoration of tropical forests: priority setting under REDD+	2012	Kettle CJ	Biological Conservation							x		
WS		Assessing the value of annual and perennial forage mixtures for bumblebees by direct observation and pollen analysis	2006	Carvell C, Westrich P, Meek WR, Pywell RF, Nowakowski M	Apidologie								x	
WS		Culture studies on early development of <i>Lessonia trabeculata</i> (Phaeophyceae, Laminariales): seasonality and acclimation to light and temperature	2013	Murua P, Westermeier R, Patino DJ, Mueller DG	Phycological Research				x					

Source					Categories								
DB	Title of paper or chapter	Date	Authors	Journal / Book	exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
WS	Mapping genetic variation and seed zones for <i>Bromus carinatus</i> in the Blue Mountains of eastern Oregon, USA	2010	Johnson RC, Erickson VJ, Mandel NL, St Clair JB, Vance-Borland KW	Botany-Botanique			x				x		
WS	Monitoring restored riparian vegetation: how can recent developments in remote sensing sciences help?	2013	Dufour S, Bernez I, Betbeder J, Corgne S, Hubert-Moy L, Nabucet J, Rapinel S, Sawtschuk J, Trolle C	Knowledge and Management of Aquatic Ecosystems						x			
WS	An invasive grass increases live fuel proportion and reduces fire spread in a simulated grassland	2013	McGranahan DA, Engle DM, Miller JR, Debinski DM	Ecosystems	x				x				
WS	Growth, herbivore distribution, and herbivore damage of timber trees in a tropical silvopastoral reforestation system	2013	Riedel J, Dorn S, Plath M, Mody K	Annals of Forest Science					x				

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
WS		Synchronous phenology of hawkmoths (Sphingidae) and <i>Inga</i> species (Fabaceae-Mimosoideae): implications for the restoration of the Atlantic forest of northeastern Brazil	2011	Cruz-Neto O, Machado IC, Duarte JAJr, Lopes AV	Biodiversity and Conservation								x	
WS		Phenological asynchronization as a restrictive factor of efficient pollination in clonal seed orchards of pedunculate oak (<i>Quercus robur</i> L.)	2011	Franjic J, Sever K, Bogdan S, Skvorc Z, Krstonosic D, Aleskovic I	Croatian Journal of Forest Engineering			x				x		
WS		Reproductive phenology of <i>Miconia mirabilis</i> (Melastomataceae) within three distinct physiognomies of Atlantic Forest, Bahia, Brazil	2012	Pessoa MS, De Vleeschouwer KM, Talora DC, Rocha L, Araujo AAM	Biota Neotropica								x	
WS		Biological flora of the British Isles: <i>Gymnadenia</i>	2012	Meekers T, Hutchings MJ, Honnay O,	Journal of Ecology					x				

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
		<i>conopsea</i> s.l.		Jacquemyn H										
WS		Landscape patterns of phenotypic variation and population structuring in a selfing grass, <i>Elymus glaucus</i> (blue wildrye)	2004	Erickson VJ, Mandel NL, Sorensen FC	Canadian Journal of Botany			x						
WS		Flower and fruit availability along a forest restoration gradient	2014	Garcia LC, Hobbs RJ, Maees dos Santos FA, Rodrigues RR	Biotropica								x	
WS		Sympatric species of <i>Hibbertia</i> (Dilleniaceae) vary in dormancy break and germination requirements: implications for classifying morphophysiological dormancy in Mediterranean biomes	2012	Hidayati SN, Walck JL, Merritt DJ, Turner SR, Turner DW, Dixon KW	Annals of Botany				x					
WS		Reproductive biology of a threatened Australian saltmarsh plant - <i>Wilsonia backhousei</i>	2012	Sommerville K, Pulkownik A, Burchett M	Aquatic Botany					x				

Source					Categories								
DB	Title of paper of chapter	Date	Authors	Journal / Book	exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
	semi-arid system												
WS	Fuel conditions associated with native and exotic grasses in a subtropical dry forest in Puerto Rico	2012	Thaxton JM, Van Bloem SJ, Whitmire S	Fire Ecology	x				x				
WS	Conservation aspects for chasmophytic species: Phenological behavior and seed strategies of the Central Apennine threatened endemism <i>Moehringia papulosa</i> Bertol.	2012	Soriano P, Estrelles E, Bianchelli M, Galie M, Biondi E	Plant Biosystems				x					
WS	Pollination and breeding systems of woody plant species in tropical dry evergreen forests, southern India	2010	Nayak KG, Davidar P	Flora							x	x	
WS	Variation in dormancy and germination in three co-occurring perennial forest herbs	2011	Albrecht MA, McCarthy BC	Plant Ecology				x					

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
WS		Evolution of critical day length for diapause induction enables range expansion of <i>Diorhabda carinulata</i> , a biological control agent against tamarisk (<i>Tamarix</i> spp.)	2012	Bean DW, Dalin P, Dudley TL	Evolutionary Applications	x							x	
WS		The phenology of dioecious <i>Ficus</i> spp. tree species and its importance for forest restoration projects	2012	Kuaraksa C, Elliott S, Hossaert-Mckey M	Forest Ecology and Management							x		
WS		From nursery into nature: a study on performance of cultivated varieties of native plants used in re-vegetation, their wild relatives and evolving wild x cultivar hybrids	2013	Schroeder R, Prasse R	Ecological Engineering		x	x						

Source					Categories								
DB	Title of paper of chapter	Date	Authors	Journal / Book	exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
	dominated grasslands												
WS	Strong natural selection during plant restoration favors an unexpected suite of plant traits	2013	Kulpa SM, Leger EA	Evolutionary Applications		x	x						
WS	Altitudinal genetic variation in <i>Pinus hartwegii</i> Lindl. I: height growth, shoot phenology, and frost damage in seedlings	2009	Viveros-Viveros H, Saenz-Romero C, Vargas-Hernandez JJ, Lopez-Upton J, Ramirez-Valverde G, Santacruz-Varela A	Forest Ecology and Management			x						
WS	Restoration of <i>Cymodocea nodosa</i> (Uchria) Ascherson seagrass meadows through seed propagation: seed storage and influences of plant hormones and mineral nutrients on seedling growth in vitro	2010	Zarranz ME, Gonzalez-Henriquez N, Garcia-Jimenez P, Robaina RR	Botanica Marina				x					

Source					Categories								
DB	Title of paper of chapter	Date	Authors	Journal / Book	exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
WS	Assessing detection probabilities of larval amphibians and macroinvertebrates in isolated ponds	2010	Curtis AE, Paton PWC	Wetlands						x			
WS	Challenges to deep-water reproduction by lake trout: pertinence to restoration in Lake Michigan	2007	Janssen J, Marsden JE, Bronte CR, Jude DJ, Sitar SP, Goetz FW	Journal of Great Lakes Research		x						x	
WS	Reproductive phenology, seed germination and ex situ conservation of <i>Pseudananas sagenarius</i> in a semi-deciduous tropical forest fragment	2010	Vieira BC, Silveira FAO	Plant Species Biology				x					
WS	Impact of grazing management on hibernating caterpillars of the butterfly <i>Melitaea cinxia</i> in calcareous grasslands	2012	van Noordwijk CGE, Flierman Daphne E, Remke Eva, WallisDeVries MF, Berg MP	Journal of Insect Conservation					x			x	

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
WS		Rangewide provenance variation in Atlantic white-cedar (<i>Chamaecyparis thyoides</i>): early survival and growth in New Jersey and North Carolina plantations	2005	Mylecraine KA, Kuser JE, Zimmermann GL, Smouse PE	Forest Ecology and Management			x						
WS		Diferencias en la produccion de frutos del roble <i>Quercus humboldtii</i> Bonpl. en dos bosque andinos de la cordillera oriental Colombiana	2010	González Melo A, Parrado Rosselli Á	Colombia Forestal					x				
WS		Day - time feeding ecology of <i>Eulemur cinereiceps</i> in the Agnalazaha Forest, Mahabo - Mananivo, Madagascar.	2010	Andriamaharoa H, Birkinshaw C, Reza L	Madagascar Conservation & Development								x	
WS		A review of the seabirds of Phillip Island in the Norfolk Island Group.	2010	Priddel D, Carlile N, Evans O, Evans B, McCoy H	Notornis								x	
WS		Germination phenology of some Great Basin	2010	Forbis TA	Plant Species Biology	x			x				x	

Source					Categories								
DB	Title of paper of chapter	Date	Authors	Journal / Book	exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
WS	Effects of spreading species-rich green hay on the botanical composition of an agriculturally improved hay meadow in northern England	2013	Kirkham FW, Bhogal A, Chambers BJ, Dunn RM, Tallwin JRB	Grass and Forage Science							x		
WS	Vegetation colonization in a restoring tidal marsh: a remote sensing approach	2008	Tuxen KA, Schile LM, Kelly M, Siegel SW	Restoration Ecology						x			
WS	Soil conditions in natural, declining and restored heathlands influence plant-pollinator interactions of <i>Calluna vulgaris</i>	2012	de la Pena E, Van De Velde H, Lens L, Bonte D	Restoration Ecology								x	
WS	Ecological aspects of aroeira (<i>Myracrodruon urundeuva</i> - Anacardiaceae): phenology and seed germination	2008	Nunes YRF, Fagundes M, Almeida HdeS, Veloso MdasDM	Revista Arvore				x					

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
WS		Monitoring the effects of forest restoration treatments on post-fire vegetation recovery with MODIS multitemporal data	2008	van Leeuwen WJD	Sensors						x			
WS		Life-history strategies and water-resource allocation in 5 pature species of the Tunisian arid zone	1992	Chaieb M, Floret C, Lefloch E, Pontanier R	Arid Soil Research and Rehabilitation					x				
WS		Recovery of native plant community characteristics on a chronosequence of restored prairies seeded into pastures in west-central Iowa	2012	Carter DL, Blair JM	Restoration Ecology				x		x	x		
WS		Selective and non-selective control of invasive plants: the short-term effects of growing-season prescribed fire, herbicide, and mowing in	2007	Simmons MT, Windhager S, Power P, Lott J, Lyons RK, Schwopce C	Restoration Ecology	x				x		x	x	

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
		two Texas prairies												
WS		Approaches to selecting native plant replacements for fleshy-fruited invasive species	2009	Gosper CR, Vivian-Smith G	Restoration Ecology								x	
WS		Long-term changes in the copepod community of Lake Geneva	2007	Anneville O, Molinero JC, Souissi S, Balvay G, Gerdeaux D	Journal of Plankton Research						x			
WS		The role of reproductive phenology, seedling emergence and establishment of perennial <i>Salix gordejevii</i> in active sand dune fields	2007	Yan Q, Liu Z, Ma J, Jiang D	Annals of Botany				x					
WS		Ecophysiology of horse chestnut (<i>Aesculus hippocastanum</i> L.) in degraded and restored urban sites	2007	Oleksyn J, Kloeppe BD, Lukasiewicz S, Karolewski P, Reich PB	Polish Journal of Ecology						x			
WS		Modalities of colonization of woody	2007	Bocquet A, Chambrey C, Derroire G, Tassin J	Revue d'Ecologie - La Terre et la Vie						x			

Source					Categories								
DB	Title of paper of chapter	Date	Authors	Journal / Book	exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
	savannah by dry forest plants in New Caledonia.												
WS	Fenologia da frutificação de espécies vegetais nativas e a restauração florestal no arquipélago de Fernando de Noronha, PE, Brasil	2013	Machado MS, Brancalion PHS, Potascheff CM, Santos AJB, Nave AG, Rodrigues RR, Gandolfi S	Hoehnea							x		
WS	Seed germination strategies of species with restoration potential in a fire-maintained pine savanna	2006	Coffey KL, Kirkman LK	Natural Areas Journal				x					
WS	Foraging ecology of parrots in a modified landscape: seasonal trends and introduced species	2008	Matuzak GD, Bezy MB, Brightsmith DJ	Wilson Journal of Ornithology								x	
WS	A paired study of prairie carbon stocks, fluxes, and phenology: comparing the world's oldest prairie restoration with an adjacent remnant	2006	Kucharik,CJ, Fayram NJ, Cahill KN	Global Change Biology						x			

Source	DB	Title of paper or chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
WS		Biological flora of the British Isles: <i>Primula vulgaris</i> Huds. (<i>P. acaulis</i> (L.) Hill)	2009	Jacquemyn H, Endels P, Brys R, Hermy M, Woodell SRJ	Journal of Ecology			x						
WS		Seasonal growth and reproduction of <i>Ruppia maritima</i> L. s.l. in Lake Pontchartrain, Louisiana, USA	2005	Cho HJ, Poirrier MA	Aquatic Botany						x	x		
WS		Characterization of diversity among 3 squirreltail taxa	2003	Jones TA, Nielson DC, Arredondo JT, Redinbaugh MG	Journal of Range Management			x						

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
WS		Comparison of common tern reproductive performance at four restored colonies along the Maine coast, 1991-2002	2004	Hall CS, Kress SW	Waterbirds						x			
WS		Flowering timing prediction in Australian native understorey species (<i>Acrotriche</i> R. Br Ericaceae) using meteorological data	2012	Schneemilch M, Kokkinn M, Williams CR	International Journal of Biometeorology			x				x		
WS		Phenology, and seed production and germination of seven endemic <i>Mimosa</i> species (Fabaceae-Mimosoideae) of the Tehuacan-Cuicatlan Valley, Mexico	2004	Camargo-Ricalde SL, Dhillion SS, Garcia-Garcia V	Journal of Arid Environments							x		
WS		Dispersal phenology of hydrochorous plants in relation to discharge, seed release time and buoyancy of seeds: the flood pulse concept	2004	Boedeltje G, Bakker JP, Ten Brinke A, Van Groenendael JM, Soesbergen M	Journal of Ecology							x		

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
		supported												
WS		Restoration of magnesian limestone grassland: optimizing the time for seed collection by vacuum harvesting	2004	Riley JD, Craft IW, Rimmer DL, Smith RS	Restoration Ecology							x		
WS		Ecological significance of seed germination characteristics in flood-meadow species	2004	Holzel N, Otte A	Flora				x					
WS		Evaluating the demographic, reproductive, and genetic value of eucalypt paddock trees for woodland restoration in agricultural landscapes	2010	Ottewell KM, Donnellan SC, Paton DC	Restoration Ecology			x						
WS		Seed germination of willow species from a desert riparian ecosystem	2003	Young JA, Clements CD	Journal of Range Management				x					

Source					Categories								
DB	Title of paper or chapter	Date	Authors	Journal / Book	exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
WS	Technical note: early harvest of squirreltail seed	2001	Doescher PS	Journal of Range Management				x			x		
WS	Initial effects of prescribed fire on morphology, abundance, and phenology of forbs in big sagebrush communities in southeastern Oregon	2003	Wroblewski DW, Kauffman JB	Restoration Ecology					x	x		x	
WS	Genetic variation and productivity of <i>Populus trichocarpa</i> and its hybrids. X. Trait correlations in young black cottonwood from four river valleys in Washington	1998	Dunlap JM, Stettler RF	Trees Structure and Function							x		
WS	Restoration of riparian meadows degraded by livestock grazing: above- and belowground responses	2002	Martin D, Chambers J	Plant Ecology					x				

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
WS		Propagating framework tree species to restore seasonally dry tropical forest: implications of seasonal seed dispersal and dormancy	2002	Blakesley D, Elliott S, Kuarak C, Navakitbumrung P, Zangkum S, Anusarnsunthorn V	Forest Ecology and Management				x					
WS		Mode of pollination, pollen germination, and seed set in smooth cordgrass (<i>Spartina alterniflora</i> , Poaceae)	2004	Fang XB, Subudhi PK, Venuto BC, Harrison SA	International Journal of Plant Sciences			x						
WS		The role of mycorrhizal fungi in competitive interactions among native bunchgrasses and alien weeds - a review and synthesis	1992	Goodwin J	Northwest Science							x		
WS		Ornamental attributes of the natural variants of <i>Cordyline australis</i>	2001	Harris W	Proceedings of the 20th International Eucarpia Symposium			x				x		
WS		Succession and fire season in experimental prairie plantings	1995	Howe HF	Ecology					x				
WS		Response of early-flowering and late-	1994	Howe HF	Ecological Applications					x				

Source					Categories								
DB	Title of paper of chapter	Date	Authors	Journal / Book	exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
	flowering plants to fire seasons in experimental prairies												
WS	Bee diversity along a disturbance gradient in tropical lowland forests of south-east Asia	2001	Liow LH, Sodhi NS, Elmqvist T	Journal of Applied Ecology								x	
WS	Seasonal cattle management in 3 to 5 year old bitterbrush stands	1999	Ganskopp D, Svejcar T, Taylor F, Farstvedt J, Paintner K	Journal of Range Management					x				
WS	Fire and seedling population dynamics in western Oregon prairies	2000	Maret MP, Wilson MV	Journal of Vegetation Science					x			x	
WS	Establishing realistic restoration targets for nutrient-enriched shallow lakes: linking diatom ecology and palaeoecology at the Attenborough Ponds, UK	2001	Sayer CD, Roberts N	Hydrobiologia						x			
WS	Influence of fire season and fire behavior on woody plants in red-cockaded woodpecker	1999	Sparks JC, Masters RE, Engle DM, Payton ME, Buehner GA	Wildlife Society Bulletin						x			

Source	DB	Title of paper of chapter	Date	Authors	Journal / Book	Categories								
						exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
		clusters												
WS		Dune restoration introduces genetically distinct American beachgrass, <i>Ammophila breviligulata</i> , into a threatened local population	2010	Holmstrom RM, Eттerson JR, Schimpf DJ	Restoration Ecology			x						
WS		Producing native seed of <i>Stipa lagascae</i> R. and Sch. in presaharian Tunisia: high yields, high genetic variation or both?	2002	Visser M, Reheul D	Genetic Resources and Crop Evolution			x				x		
WS		Restoring depleted Tunisian drylands with native steppic species: where should we source the seeds?	2001	Visser M, Reheul D	Genetic Resources and Crop Evolution			x				x		
WS		Produção de mudas de espécies das restingas do município do Rio de Janeiro, RJ, Brasil	2004	Zamith LR, Scarano FR	Acta Botanica Brasilica							x		

Source					Categories								
DB	Title of paper of chapter	Date	Authors	Journal / Book	exotic species	functions/traits	genetic provenance	germination	management	monitoring	seed h p m	sp interactions	lack of knowledge
WS	Spontaneous interspecific hybridization and patterns of pollen dispersal in ex-situ populations of a tree species (<i>Sinojackia xylocarpa</i>) that is extinct in the wild	2010	Zhang JJ, Ye QG, Yao XH, Huang HW	Conservation Biology			x				x		

Appendix S2 - Figure S1. Flow chart detailing the process of paper collection and elimination for the study. A. for book chapters, B. for *Restoration Ecology* and C. for *Web of Science* (up to February 2014).

Appendix S2 - Figure S2. Example of application of phenology to restoration based on a study by Alvarado et al. (2014) carried out with the following reference ecosystem: *Uapaca bojeri* (tapia) woodlands, Highlands of Madagascar. Solid lines represent phenological information from these studies. Dotted lines represent future phenological studies that would enhance subsequent restoration steps. Human society may depend on restored sites for their subsistence, and restored sites are more likely to be well maintained by local human populations if they provide sustainable incomes. Restoration would extend the area of this species-rich ecosystem, which plays an important role in the local economy as a source of edible fruits, mushrooms and medicinal plants, and as a habitat for wild silk worms (*Borocera madagascariensis*), whose cocoons are collected by local residents to produce cloth (Alvarado et al. 2012, 2015).

Literature cited for Figure S2

Alvarado ST, Buisson E, Rabarison H, Birkinshaw C; Lowry II PP (2012) Ibity Mountain, Madagascar: background and perspectives for ecological restoration. *Ecological Restoration* 30:12-15.

Alvarado ST, Buisson E, Rabarison H, Rajeriarison C, Birkinshaw C, Lowry II PP (2015) Management plans: keystones for the creation of new protected areas, the case of Ibity Massif, Madagascar. *Tropical Conservation Science* 8:367-395.

Alvarado ST, Buisson E, Rabarison H, Rajeriarison C, Birkinshaw C, Lowry II PP, Morellato LPC (2014) Fire and the reproductive phenology of endangered Madagascar sclerophyllous tapia woodlands. *South African Journal of Botany* 94:79-87.