

1 **Supplementary material**

2

3 **Supplementary material S1**

4 The 11 basic operations (BO) used to characterize the maritime pine breeding cycle are
5 described in detail below.

6 **BO#1 Crosses (Years 1-3)**

7 The first operation is the crossing of the initial parents in the clonal archives. Bags (10 per
8 cross) are placed over female flowers at the end of March (year 1) to prevent them from
9 being pollinated by other trees. Pollen is collected in April and inserted into the bags two or
10 three times. The bags are removed at the end of year 1. The cones are harvested 18 months
11 later (November, year 2). For all these operations, the technicians used a boom lift to reach
12 the female flowers. Once harvested, the cones are opened by heating in an oven and the
13 seeds are then extracted and stored in a cold room (start of year 3).

14 **BO#2 Seedlings (Year 3)**

15 Harvested seeds are sown in peat clods in the nursery in June, with the aim of obtaining 60
16 seedlings per cross. Seedlings are labeled and grown until October, when they are 15
17 centimeters tall and ready for plantation.

18 **BO#3 Progeny trial (Year 4)**

19 The seedlings are planted in forest plots according to a randomized plot design for further
20 phenotypic evaluation. Trials are established between the end of winter and spring. Great
21 care is taken to record the position of each seedling and its identity; a mortality survey is
22 performed in October (mortality rates are generally below 10%).

23 **BO#4 Evaluation 1 (Year 12)**

24 Trees are evaluated at the age of eight years, before thinning. Measurements are made
25 during the winter (outside the growing season). Pruning is performed beforehand to make it
26 easier to take measurements in the stand: all branches at a height of less than 2 m high are
27 cut (the trees are approximately 7-8 m high). The trees are evaluated on the following

28 criteria: circumference at breast height, total tree height, stem straightness, sanitary
29 conditions (pine twist rust, *Dioryctria sylvestrella* attacks), branching quality.

30 **BO#5 Evaluation 2 (Year 16)**

31 A second evaluation is performed at the age of 12 years, after thinning. As for the evaluation
32 at eight years, measurements are made during the winter. Trees are evaluated for
33 circumference at breast height, total height, wood density and wood grain angle.

34 **BO#6 Genotyping (Year 16)**

35 Needles are collected from a subset of selected trees and used for DNA extraction.
36 Genotyping is performed with a set of 62 SNPs in the Sequenom MassARRAY iPLEX Gold
37 assay (Sequenom, San Diego, CA, USA) at the genotyping and sequencing facility of
38 Bordeaux, France (<https://pgtb.fr/>). Genotyping analyses are performed with Cervus software
39 (Kalinowski et al. 2007; Marshall et al. 1998) to check the identity of the trees or to determine
40 their paternity (for PMX and OP strategies).

41 **BO #7 Scion collection (Year 16)**

42 Phenotyping evaluation and genotyping results are used for a BLUP evaluation leading to the
43 selection of trees from the progeny trial. For each selected tree, 20 scions are collected, with
44 the objective of obtaining a total of eight successful grafts per genotype. The scions are
45 harvested by climbers in February to ensure that the buds are dormant, and they are placed
46 in cold storage.

47 **BO#8 Grafting (Year 16)**

48 The next step is the grafting of the selected genotypes. The rootstocks are previously grown
49 for two years in the nursery and are in their third year, ready for grafting. Grafting is
50 performed in May. Graft weaning, the elimination of the unnecessary parts of the rootstock, is
51 then performed and the grafted plants are ready for planting in October.

52 **BO#9 Plantation in clonal archives (Year 16)**

53 The grafted plants are planted in the clonal archives in November-December in a tilled soil.
54 Protections are placed around the plants to prevent damage by wild animals. Eight copies
55 per clone are installed in two clonal archives.

56 **BO#10 Pruning in the clonal archives (Year 27)**

57 Pruning is performed in the clonal archives when the trees are 11 years old.

58 **BO#11 Clonal archive maintenance (Years 16-56)**

59 Finally, clonal archive maintenance involves mulching 15 times between the planting of the
60 trees and the time point at which the trees reach the age of 40 years.

61 **Overall management of the breeding program**

62 The management of the breeding program includes the choice of crosses to be performed,
63 the design of the progeny trials and the evaluation of breeding value. Management costs
64 relate to personnel costs and the cost of the software used for genetic analyses. The costs
65 associated with management are assumed to be fixed and independent of the size and type
66 of breeding program.

67

68 **Supplementary Table S2**

69 Size of breeding scenarios simulated and genetic gains achieved at cycle 5 for various total
 70 costs (CT^{REF} , $CT^{REF/2}$ and CT^{REFx2}). N_C , N_R , N_P and N_G are the number of crosses (CC and
 71 PMX strategies) or cones collected (OP strategy), the size of the population recruited, the
 72 number of parents and the number of genotyped trees, respectively.

Breeding scenario	Total cost	Size variables				Distribution of total cost					Number of families *	Number of offspring per family	Genetic gains at cycle 5 (SD)
		N_C	N_R	N_P	N_G	Crosses	Candidates	Parents	Genotyping	Fixed costs			
CC150	CT^{REF}	150	15000	150	165	15,6%	52,8%	22,5%	0,4%	8,7%	150 FS	100	79,4% (3,2%)
PMX150	CT^{REF}	150	14590	150	750	15,6%	51,4%	22,5%	1,9%	8,7%	150 HS	97	77,4% (2,9%)
PMX50	$CT^{REF/2}$	50	5704	100	500	10,4%	40,2%	30,0%	2,5%	17,4%	50 HS	114	-**
CC50	$CT^{REF/2}$	50	5978	100	110	10,4%	42,1%	30,0%	0,5%	17,4%	50 FS	120	-**
PMX100	$CT^{REF/2}$	100	4226	100	500	20,8%	29,7%	30,0%	2,5%	17,4%	100 HS	42	55,8% (2,5%)
CC100	$CT^{REF/2}$	100	4500	100	110	20,8%	31,7%	30,0%	0,5%	17,4%	100 FS	45	-**
PMX50	$CT^{REF/2}$	50	3401	150	750	10,4%	23,9%	44,9%	3,7%	17,4%	50 HS	68	56,0% (5,0%)
CC50	$CT^{REF/2}$	50	3812	150	165	10,4%	26,8%	44,9%	0,8%	17,4%	50 FS	76	-**
PMX100	$CT^{REF/2}$	100	1923	150	750	20,8%	13,5%	44,9%	3,7%	17,4%	100 HS	19	56,8% (3,7%)
CC100	$CT^{REF/2}$	100	2334	150	165	20,8%	16,4%	44,9%	0,8%	17,4%	100 FS	23	60,8% (2,9%)
PMX150	CT^{REFx2}	150	43023	150	750	7,8%	75,7%	11,2%	0,9%	4,4%	150 HS	287	85,7% (3,9%)
CC150	CT^{REFx2}	150	43434	150	165	7,8%	76,4%	11,2%	0,2%	4,4%	150 FS	290	85,9% (3,0%)
CC300	CT^{REFx2}	300	38999	150	165	15,6%	68,6%	11,2%	0,2%	4,4%	300 FS	130	88,8% (2,1%)
PMX150	CT^{REFx2}	150	36113	300	1500	7,8%	63,5%	22,5%	1,9%	4,4%	150 HS	241	91,7% (2,3%)
CC150	CT^{REFx2}	150	36934	300	330	7,8%	65,0%	22,5%	0,4%	4,4%	150 FS	246	90,5% (3,0%)
PMX300	CT^{REFx2}	300	31679	300	1500	15,6%	55,7%	22,5%	1,9%	4,4%	300 HS	106	91,7% (3,2%)
CC300	CT^{REFx2}	300	32500	300	330	15,6%	57,2%	22,5%	0,4%	4,4%	300 FS	108	95,0% (3,3%)

73

74 * full-sib (FS) or half-sib (HS) families

75 ** diversity constraints cannot be fulfilled

76

77

78 **Supplementary material S3**

79 In the French maritime pine breeding program, a new generation of improved FRM is
80 deployed approximatively every 15 years. We compile here the Net Present Value (NPV)
81 from a series of 5 successive 15 years-long breeding cycles. The methodology used here
82 shares some similarities with the one used by Chamberland et al. (2020) and Chang et al.
83 (2019a). The main differences are the following ones:

84 - Chamberland et al. (2020) and Chang et al. (2019a) analyze the economic gain resulting
85 from one breeding cycle. The economic gain is compiled per unit of surface on an infinite
86 time horizon, by using the Land Expectation Value (LEV). In our analysis, we consider a
87 finite time corresponding to 5 successive breeding cycles. The length of the breeding
88 cycle (15 years) being shorter than the rotation length (40 years), a unit of land will be
89 replanted each time with a new generation of FRM. We thus compile the economic gain
90 per rotation with a specific FRM each time.

91 - Chamberland et al. (2020) and Chang et al. (2019a) use forest growth model to compile
92 the added merchantable volume of wood that provides the economic gain from breeding.
93 Here we use a simpler formulation and make directly an assumption on the yield gain.
94 Our results are compared with those obtained by Serrano-Leon et al (2021) that compile
95 the economic gain associated with the use improved FRM for different species including
96 maritime pine.

97 As it is common, the Net Present Value of a series of breeding programs is compiled as the
98 difference of value of production between a case with no breeding program (scenario 0) and
99 a case with a breeding program, taking into account the cost of this program (scenario 1). In
100 the case considered here the timing of length of breeding cycle is unchanged and we
101 suppose that the genetic gain does not affect silviculture practices both in terms of
102 operations and timing. Because of that we neglect the terms that are common in both
103 scenario:

104 - We ignore the economic gain from the use of unimproved material before the
 105 introduction of the first generation of improved material in scenario 1. This gain is indeed
 106 identical in scenario 0.

107 - We ignore the cost associated with seed orchard set up and management and the cost
 108 associated with seedling production because we suppose that they are identical in both
 109 scenarios and occurs at the same dates. We only take into account the R&D cost related
 110 to breeding.

111 **1. Discounted value over one rotation**

112 A rotation lasts T years. There are K thinnings during the rotation, each of them occurring at
 113 year t_k having a yield y_k and a wood price P_k . P_k is lower compared to the wood harvested at
 114 the end of the rotation. The final cut, which occurs at year T , has a yield y and a price P .

115 The value of production per ha over one rotation, discounted at the plantation date (r is the
 116 discount rate), is:

$$VR = \sum_{k=1}^K \frac{y_k P_k}{(1+r)^{t_k}} + \frac{y P}{(1+r)^T}$$

117 If we define: $s_k = \frac{y_k P_k}{y P}$, we get:

$$VR(y) = \sum_{k=1}^K \frac{s_k y P}{(1+r)^{t_k}} + \frac{y P}{(1+r)^T} = \underbrace{\left(1 + \sum_{k=1}^K s_k (1+r)^{T-t_k} \right)}_{A_R} \frac{y P}{(1+r)^T}$$

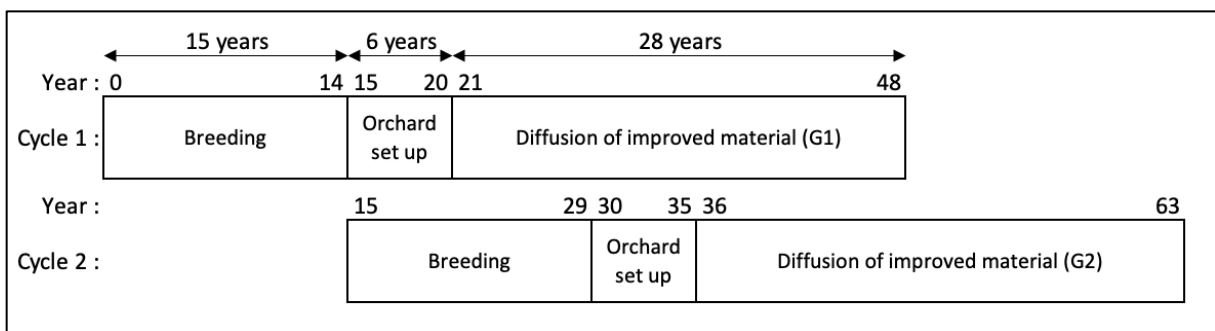
118 The coefficient A_R thus captures the added value provided by the thinnings, taking into
 119 account the yield of each thinning, the price difference and the fact that thinnings occurs
 120 earlier in the production cycle ($A_R=1$ would be the extreme case where thinning provides no
 121 added value). In the rest of the analysis, we suppose that an increase in the yield of the final
 122 cut affects, with the same proportion the yield of the different thinnings.

123 **2. Discounted value over one breeding cycle and generation of improved material**

124 Figure S3.1 summarizes the succession of breeding cycles that we consider here. Each
 125 cycle is divided in three phases:

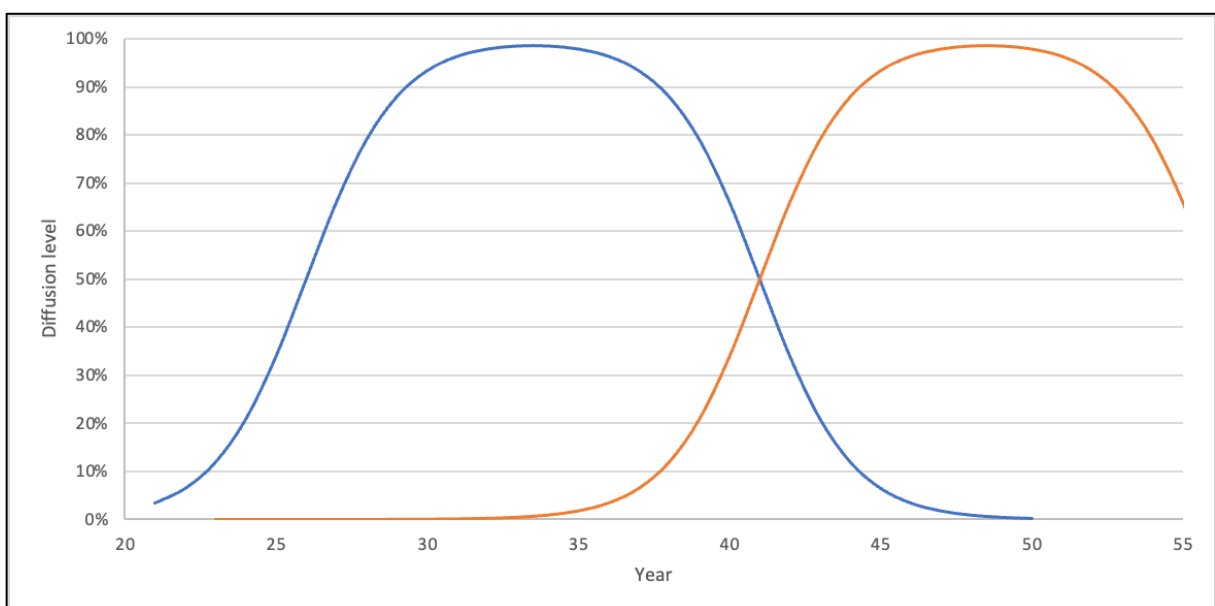
- 126 - A breeding program of 15 years. The total cost of this research investment, discounted
127 at the first year of the cycle is CT .
- 128 - The set-up of a seed orchard that lasts 6 years. We ignore the cost associated with seed
129 orchard because they are equivalent for any type of material.
- 130 - The diffusion of improved material. Each year a surface ($S \theta_t$) of improved material from
131 this generation is planted, S being the total surface planted each year and θ_t the diffusion
132 level of this generation. θ_t first increases because the latest improved material replaces
133 the previous generation, and then decreases because it is replaced by the next
134 generation. Figure S3.2 illustrates the diffusion level of the first two generations.

135 **Figure S3.1.** Succession of breeding cycles considered for the NPV analysis
136



137

138 **Figure S3.2.** Diffusion level of the two first generations of improved material (θ_t)
139



140

141

142 If we consider one cycle covering these three phases the net present value, discounted at
 143 the date of the beginning of the cycle, we get:

$$VG = -CT + \sum_{t=21}^{t=48} \frac{S \theta_t VR(y_t)}{(1+r)^t}$$

144 We suppose that during the first years of the seed orchard production, pollen flow leads to
 145 have seed with a yield potential that is lower than the maximum yield potential. To take that
 146 into account, we suppose that the yield for the rotation planted at year t is the maximum yield
 147 potential (y) for the FRM generation we consider multiplied by a parameter (α_t) that increases
 148 over time. Developing $VR(\alpha_t y)$, we get:

$$VG(y) = -CT + \sum_{t=21}^{t=48} \frac{S \theta_t A_R \alpha_t y P}{(1+r)^{t+T}} = -CT + \frac{S A_R y P}{(1+r)^T} \underbrace{\left(\sum_{t=21}^{t=48} \frac{\theta_t \alpha_t}{(1+r)^t} \right)}_{A_G}$$

149 3. Discounted value over a series of cycles

150 We now consider a series of 5 successive cycles, the time lag between each cycle (τ) being
 151 the duration of one breeding cycle (here 15 years). The value associated with 5 successive
 152 cycles, discounted at the date of the beginning of the first cycle is:

$$V = \sum_{n=1}^5 \frac{VG(y_n)}{(1+r)^{\tau(n-1)}}$$

153 Each breeding cycle leads to an increase of both the volume (y) and the quality of wood.
 154 Hence both the yield and the price are increasing at each cycle. Replacing $VG(y_n)$ by the
 155 value compiled above, we get:

$$V = -CT \underbrace{\left(\sum_{n=1}^5 \frac{1}{(1+r)^{\tau(n-1)}} \right)}_{A_I} + \frac{S A_R A_G}{(1+r)^T} \left(\sum_{n=1}^5 \frac{y_n P_n}{(1+r)^{\tau(n-1)}} \right)$$

156 The net present value of the research investment over these five breeding cycles is equal to:

$$NPV = V(\{y_1, y_2, y_3, y_4, y_5\}) - V(y_0)$$

157 The detailed expression being:

$$NPV = -A_I I + \frac{S A_R A_G}{(1+r)^T} \left(\sum_{n=1}^5 \frac{y_n P_n - y_0 P_0}{(1+r)^{\tau(n-1)}} \right)$$

158 **4. Parameters values**

159 Based on the French maritime pine breeding program, we used the parameters defined in
 160 the three tables below to estimate the NPV (Table S3.1, Table S3.2 and Table S3.3).

161

162 **Table S3.1.** General parameters

Parameter		Value
P	Wood unit price	30 €/m ³ and 50€/m ³
P_n/P_{n-1}	Relative price increase per cycle	1 or 1.1
y_0	Yield under scenario 0	260 m ³ /ha
r	Discount rate	3%; 4% and 5%
S	Surface planted with FRM	25 000 ha/year
T	Revolution duration	40 years
CT	Total research cost per cycle	CT ^{REF} = 700K€ CT ^{REF/2} = 350K€ CT ^{REFx2} = 1.4M€

163

164 **Table S3.2.** Thinning yield and relative price

Thinning #	t_k	$(1+r)^{T-tk}$	y_k	P_k/P	s_k
1	12				
2	16	2.563	60	0.6	0.186
3	22	2.026	80	0.7	0.215
4	32	1.369	80	0.9	0.277

165 With $r=4\%$ and $y=260$ we get $A_R = 1 + 2.563*0.186 + 2.026*0.215 + 1.369*0.277 = 2.170$

166

167 **Table S3.3.** Parameter α_t depending on the year t

t	21	22	23	24	25	26	≥ 27
α_t	0.55	0.65	0.75	0.80	0.85	0.90	0.95

168

169 To compile A_G , we use the diffusion level presented in Figure S3.2. The parameter α_t is

170 defined in Table S3.3 with $r=4\%$. We thus get:

$$A_G = \sum_{t=21}^{t=48} \frac{\theta_t \alpha_t}{(1+r)^t} = 3.832$$

171 The NPV per year is defined as constant flow over time over the whole time horizon which

172 corresponds here to 108 years. It is thus the NPV divided by $\sum_{t=0}^{108} \frac{1}{(1+r)^t}$. This sum is equal to

173 32.96 for $r=3\%$, 26.64 for $r=4\%$ and 20.90 for $r=5\%$.

174 **5. Additional results**

175 The Table S3.4 provides the estimated NPV with two discount rates equal to 3% and 5%

176 (see Table 4 for results with a discount rate equals to 4%).

177

178 **Table S3.4.** Estimated Net Present Value (two discount rates considered) based on no price

179 increase due to wood quality improvement ($P_n/P_{n-1}=1$)

r	CT	P	NPV (M€)	NPV/ha (€)	NPV/ha/an (€)
3%	CT ^{REF}	30	414.52	16 581	503
3%	CT ^{REF}	50	692.03	27 681	840
3%	CT ^{REF/2}	30	300.26	12 010	364
3%	CT ^{REF/2}	50	501.01	20 041	608
3%	CT ^{REFx2}	30	467.92	18 717	568
3%	CT ^{REFx2}	50	782.18	31 287	949
5%	CT ^{REF}	30	76.24	3 050	146
5%	CT ^{REF}	50	127.95	5 118	245
5%	CT ^{REF/2}	30	54.92	2 197	105
5%	CT ^{REF/2}	50	91.97	3 679	176
5%	CT ^{REFx2}	30	84.23	3 369	161
5%	CT ^{REFx2}	50	142.14	5 685	272

180

181 The Table S3.5 provides the estimated NPV with three discount rates levels (3%, 4% and
 182 5%) under the scenario that wood quality improvement at each generation leads to a price
 183 increase of 10%.

184

185 **Table S3.5.** Estimated Net Present Value (three discount rates considered) based on price
 186 increase due to wood quality improvement ($P_n/P_{n-1}=1.1$)

r	CT	P	NPV (M€)	NPV/ha (€)	NPV/ha/an (€)
4%	CT ^{REF}	30	377.79	15 112	589
4%	CT ^{REF}	50	630.65	25 226	984
4%	CT ^{REF/2}	30	315.97	12 639	493
4%	CT ^{REF/2}	50	527.12	21 085	822
4%	CT ^{REFx2}	30	405.66	16 226	633
4%	CT ^{REFx2}	50	678.09	27 124	1 058
3%	CT ^{REF}	30	923.44	36 937	1 121
3%	CT ^{REF}	50	1 540.22	61 609	1 869
3%	CT ^{REF/2}	30	773.56	30 942	939
3%	CT ^{REF/2}	50	1 289.84	51 594	1 565
3%	CT ^{REFx2}	30	996.66	39 867	1 209
3%	CT ^{REFx2}	50	1 663.43	66 537	2 018
5%	CT ^{REF}	30	163.08	6 523	312
5%	CT ^{REF}	50	272.68	10 907	522
5%	CT ^{REF/2}	30	136.29	5 452	261
5%	CT ^{REF/2}	50	227.58	9 103	436
5%	CT ^{REFx2}	30	173.88	6 955	333
5%	CT ^{REFx2}	50	291.55	11 662	558

187

188

189 **Supplementary Table S4**

190 The table below summarizes, for each basic operation (BO), the unit cost and the proportion
 191 of the total cost associated with each type of cost (personnel, consumables, equipment
 192 depreciation, rental and services). These estimates are based on the maritime pine breeding
 193 activities performed annually at INRAE.

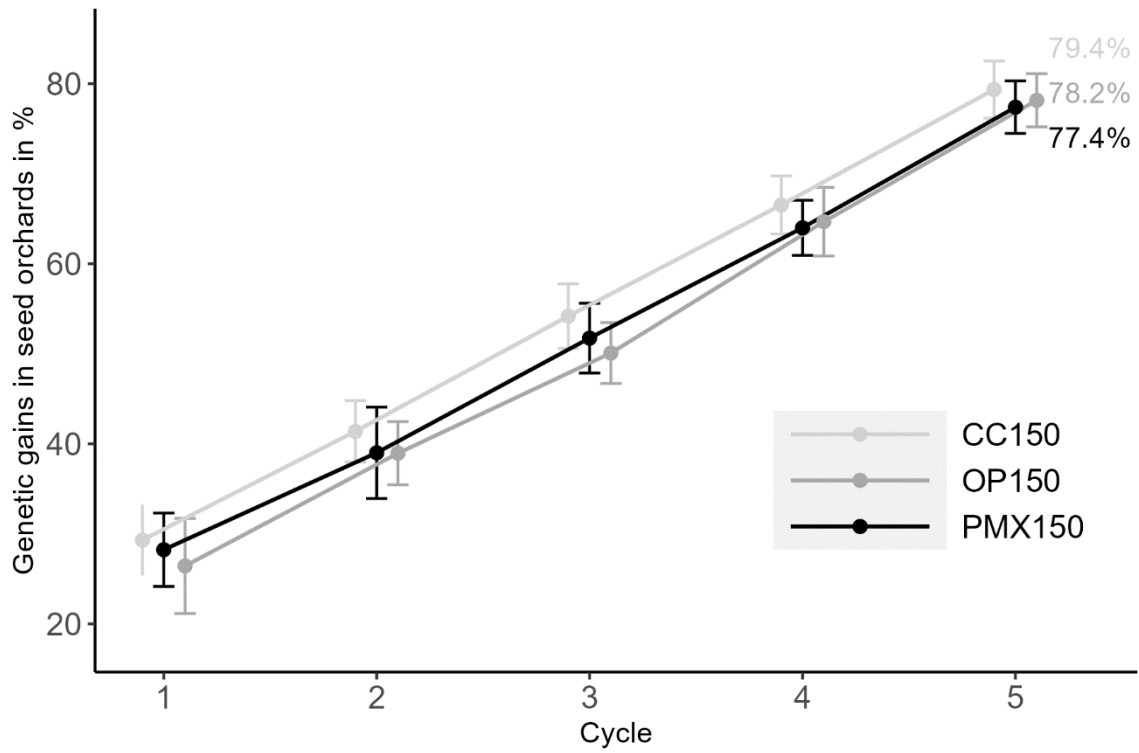
BO#	Description	Unit cost	Personnel	Consumables	Depreciation of equipment	Rental and services
1	Crosses	369.5	78%	8%	2%	12%
2	Seedlings	2.3	81%	10%	10%	0%
3	Progeny trial	6.6	97%	2%	1%	0%
4	Evaluation 1	4.3	78%	0%	4%	18%
5	Evaluation 2	3.0	89%	0%	11%	0%
6	Genotyping	15.8	45%	55%	0%	0%
7	Selection	255.7	92%	0%	8%	0%
8	Grafting	304.8	93%	7%	0%	0%
9	Plantation in clonal archives	242.9	72%	16%	12%	0%
10	Pruning in clonal archives	34.4	42%	23%	0%	35%
11	Clonal archive maintenance	14.0	52%	24%	24%	0%
-	Overall management	46,017.0	70%	30%	0%	0%

194

195

196 **Supplementary Figure S5**

197 Genetic gains over the 5 breeding cycles for scenarios CC150, PMX150 and OP150 for the
198 total cost CT^{REF} .



199

200