Supplementary Materials

for article

Duration of climate change mitigation benefits from increasing boreal forest harvest age by 10 years

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1. Dynamic carbon stocks equations

Estimated parameter values for equations (1), (3), and (4) are presented in Table S3. In keeping with the decadal representation of yield curves commonly used in Ontario, parameters correspond to 10-year changes in carbon stocks starting from stand age 5 (e.g., 5, 15, 25, etc.). Table S3 includes parameter values for equations used to estimate carbon in biomass of live trees, understory vegetation, and soil, which are the metric equivalents of those in FORCARB-ON2 (i.e., tonne of carbon per hectare and cubic metre per hectare). Note that equations and parameter values for calculation of carbon stocks in total live tree biomass, understory and soil are from [24–25] while equations and parameters for calculation of carbon stocks in standing dead trees, down dead wood and forest floor are developed in this study. For consistency with previous estimates of carbon stocks in Ontario (e.g., [23]), some parameter values were retained from the original version of FORCARB despite minor updates in FORCARB-ON2 [24].

Table S1. Equations and parameter values for estimating carbon in six forest pools in Ontario forests: live tree biomass, standing dead trees, down dead wood, forest floor, understory, and soil. Carbon stocks are expressed in tonnes of carbon per hectare (t C·ha^{-1}).

Parameter	Species group			
	Pines	**Spruce-fir**	Aspen-birch	Maple-beech
Total live tree biomass, *B(t)*				
$B(t) = l_1 \cdot (l_2 + 1 - \exp(-\frac{V(t)}{l_3}))$				
Notes: 1. *V*(*t*) is volume density 2. For younger age classes with V(t)=0, B(t) is linearly interpolated between zero and the first age class with V(t)>0				
l_1	216.04	195.94	181.27	175.01
l_2	0.0346	0.0582	0.0524	0.0496
l_3	373.20	278.85	270.08	187.03
Standing dead trees, *StD(t)*				
$StD(t) = s_1 \cdot B(t-10) + s_2 \cdot (B(t) - B(t-10) \| if\ > 0) + s_3 \cdot StD(t-10)$ $StD(5) = s_0 \cdot B(5)$				
Notes: 1. s_0 is estimated carbon in standing dead trees after fire 2. For a post harvest-stand, carbon in standing dead trees is estimated based on the pre-harvest stand (either a specific stand or the average for a typical range of harvest ages)				
s_0	0.3818	0.1517	0.4176	0.1189
s_1	0.0353	0.0563	0.0994	0.0646
s_2	0.1133	0.1513	0.2602	0.1435
s_3	0.5000	0.5000	0.3700	0.3700
Down dead wood, *DDW(t)*				
$DDW(t) = d_1 \cdot B(t-10) + d_2 \cdot (1 - s_3) \cdot StD(t-10) + d_3 \cdot DDW(t-10)$ $DDW(5) = d_0 \cdot B(5)$				
Notes: 1. d_0 is estimated carbon in down dead wood after fire 2. For a post harvest-stand, carbon in down dead wood is estimated based on the pre-harvest stand (either a specific stand or the average for a typical range of harvest ages)				
d_0	0.1223	0.1210	0.1180	0.1170
d_1	0.0100	0.0100	0.0100	0.0100
d_2	0.5518	0.3429	0.3700	0.5984
d_3	0.7500	0.7500	0.5000	0.5000

Forest floor, *FF(t)*				
$FF(t) = f_1 \cdot B(t-10) + f_2 \cdot (1-d_2) \cdot (1-s_3) \cdot StD(t-10) + f_3 \cdot (1-d_3) \cdot DDW(t-10) + f_4 \cdot FF(t-10)$ $FF(5) = Dist \cdot f_0 \cdot \sqrt{f_4}$ Notes: 1. Square root of f_4 corresponds to retention rate over a 5-year period 2. *Dist* is equal to 1.0 and 0.4 for post-harvest and post-fire stands, respectively; f_0 is used if the amount of carbon in the pre-harvest / pre-fire stand is unknown				
f_0	13.80	33.70	10.20	27.70
f_1	0.0719	0.2625	0.0263	0.2574
f_2	0.3307	0.5435	0.5238	0.2529
f_3	0.7000	0.7000	0.7000	0.7000
f_4	0.4790	0.4790	0.4790	0.4790
Understory, *U(t)*				
$U(t) = u_0 + u_1 \cdot V(t) + (u_2)^2 \cdot (V(t))^2$ Note: 1. *V*(*t*) is volume density				
u_0	2.2092	2.5914	2.3291	1.6880
u_1	-0.0040	-0.0305	-0.0078	-0.0083
u_2	1.007E-05	1.534E-04	3.777E-05	5.654E-05
Soil, *SC(t)*				
$SC(t) = sc_0$ Notes: 1. *SC(t)* is assumed to be constant if species composition does not change 2. If species composition changes, transition from the "old" to the "new" value of soil carbon stock is linearly interpolated for a 50-year period				
sc_0	44.0	58.2	61.0	108.4

The parameter *Dist* for estimation of forest floor at the time of disturbance is used to account for carbon losses during fire (hence, *Dist* = 1.0 if a stand was harvested). In a meta-analysis of fire effects on carbon stocks in temperate forests, Nave et al. [81] estimated an average loss of 69% of forest floor mass by combustion from wildfires. Estimates of forest floor losses due to boreal forest fires appear to be slightly lower. For example, Neff et al. [82] reported soil organic horizon carbon stock losses of 49% after wildfire in a black spruce stand in Alaska. De Groot et al. [83] studied fuel consumption in 7 wildfires across Canada and estimated average forest floor consumption of about 60%. Respective estimates for carbon losses during prescribed burning are consistently lower [81,83–84]. Since *Dist* is used to initialize forest floor carbon stocks after wildfire, we assumed the estimate from [83] was closest to conditions in Ontario.

2. Forest units

Table S1 includes a description and species composition of 36 forest units (FU) used to assess climate change mitigation benefits from increasing harvest age by 10 years. FU names correspond to those used in Forest Management Plans (FMP). Species composition indicates the average fraction (%) of merchantable volume of each species in the total merchantable volume of the stand. For example, species composition for FU BW1 in Hearst Forest is Sb08 Sw08 Bf05 Po31 Pb08 Bw40, meaning that on average both black spruce and white spruce account for 8% of total merchantable volume of the stands classified as BW1, balsam fir accounts for 5% of total merchantable volume, etc.

Table S2. Description and species composition of forest units in Hearst Forest, Lakehead Forest, and Pic River Forest

Name	Description	Species composition
Hearst Forest		
BW1	White birch-dominated stands	Sb08 Sw08 Bf05 Po31 Pb08 Bw40
LC1	Lowland mixtures of black and white spruce, and other conifers	Sb46 Bf02 Ce20 Oc30 Po01 Bw01
LH1	Lowland hardwood stands, predominantly balsam poplar	Sb09 Sw06 Bf06 Ce02 Oc01 Po19 Pb51 Bw06
MW1	Mixedwood stands	Pj09 Sb23 Sw06 Bf04 Ce01 Po40 Pb09 Bw08
MW2C	Mixedwood stands, about 60% conifers and 40% hardwoods	Pj02 Sb30 Sw11 Bf11 Ce01 Oc01 Po28 Pb10 Bw06
MW2H	Mixedwood stands, about 60% hardwoods	Sb16 Sw10 Bf09 Ce01 Po43 Pb14 Bw07
PJ1	Jack pine-dominated stands	Pj87 Sb10 Sw01 Po02
PJ2	Jack pine-dominated stands with admixture of black spruce and some hardwoods	Pj75 Sb16 Sw01 Bf01 Po06 Pb01
PO1	Poplar-dominated hardwood stands	Pj02 Sb06 Sw05 Bf04 Po61 Pb15 Bw07
SB1	Black spruce-dominated stands	Sb89 Bf01 Ce01 Oc06 Po02 Pb01

SB3	Black spruce-dominated stands; site class lower than SB1	Sb88 Bf01 Ce02 Oc09
SF1	Upland conifer stands	Pj02 Sb32 Sw17 Bf18 Ce04 Oc03 Po15 Pb04 Bw05
SP1	Upland conifer stands	Pj09 Sb66 Sw02 Bf02 Oc01 Po15 Pb03 Bw02
Lakehead Forest		
BfMix	Mixedwood stands with large fraction of balsam fir	Pw02 Pj09 Sb23 Sw13 Bf28 Ce04 Po12 Bw09
BwDom	White birch-dominated stands	Pj02 Sb09 Sw02 Bf07 Po21 Bw59
ConMx	Mixedwood stands, more than 50% conifers	Pw02 Pj25 Sb32 Sw04 Bf06 Ce02 Po16 Bw13
HrdMx	Mixedwood stands, more than 50% hardwoods	Pw02 Pj12 Sb14 Sw06 Bf09 Ce01 Po35 Bw21
HrDom	Hardwood-dominated stands	Pj06 Sb06 Sw03 Bf07 Po59 Bw19
OcLow	Lowland conifer stands	Sb29 Sw02 Bf02 Ce34 Oc26 Po02 Bw05
PjDom	Jack pine-dominated stands	Pj88 Sb08 Po03 Bw01
PjMix	Jack pine-dominated stands with admixture of black spruce and some hardwoods	Pw01 Pr01 Pj71 Sb13 Sw02 Bf02 Po07 Bw03
PoDom	Poplar-dominated hardwood stands	Pj03 Sb03 Sw02 Bf04 Po83 Bw05
PrwMx	White and red pine-dominated stands	Pw33 Pr45 Pj04 Sb02 Sw01 Bf02 Po09 Bw04
SbDom	Upland black spruce-dominated stands	Pj02 S83 Bf03 Ce01 Oc01 Po03 Bw07
SbLow	Lowland black spruce-dominated stands	Sb80 Bf01 Ce05 Oc10 Po01 Bw03
SpMix	Mixedwood stands	Pw02 Pj20 Sb42 Sw12 Bf03 Ce05 Oc02 Po07 Bw07
Pic River Forest		
BW1	White birch dominated stands	Pj02 Sb16 Sw15 Bf01 Po22 Bw44
LC1	Mixtures of black spruce, larch, and eastern white cedar	Sb59 Sw01 Ce23 Oc14 Po01 Bw02
MW1	Mixedwood stands	Pj29 Sb22 Sw02 Po34 Bw13
MW2	Mixedwood stands	Pj01 Sb37 Sw23 Bf02 Ce01 Po19 Bw17
PJ1	Jack pine-dominated stands	Pj77 Sb16 Po06 Bw01
PJ2	Jack pine-dominated stands with admixture of black spruce and some hardwoods	Pj49 Sb35 Po10 Bw06
PO1	Poplar-dominated hardwood stands	Pj03 Sb12 Sw06 Po71 Bw08
SB1	Black spruce-dominated stands	Pj01 Sb91 Sw02 Ce01Oc02 Po02 Bw01
SF1	Mixed conifer stands of black and white spruce, balsam fir, and eastern white cedar	Pj01 Sb52 Sw17 Bf16 Ce01 Po04 Bw09
SP1	Upland black spruce-dominated stands	Pj23 Sb65 Sw02 Po08 Bw02

Pw – white pine (*Pinus strobus* L.)
Pr – red pine (*Pinus resinosa* Ait.)
Pj – jack pine (*Pinus banksiana* Lamb.)
Sb – black spruce (*Picea mariana* (Mill.) BSP)
Sw – white spruce (*Picea glauca* (Moench) Voss)
Bf – balsam fir (*Abies balsamea* L.)
Ce – eastern white cedar (*Thuja occidentalis* L.)
Oc – other conifers (e.g., larch *Larix laricina* (Du Roi) K. Koch)
Po – poplar (trembling aspen) (*Populus tremuloides* Michx.)
Pb – balsam poplar (*Populus balsamifera* L.)
Bw – white birch (*Betula papyrifera* Marshall)
Oh – other hardwoods (e.g., yellow birch *Betula alleghaniensis* Britton)

3. Successional transitions

Yield curves for FUs included in FMPs provide volume estimates for stand ages 5–255 years. The fate of older stands (either approaching 255 years or surviving past this age) is defined by FMP-specific forest successional transitions: for each FU one or more transitions are possible and these are specified as the fraction of area that at a given age succeeds from one FU into another, along with the age of the post-transition FU. As an example, Table S2 presents successional transition rules for forest unit SP1 in the Pic River Forest shown in Fig.3 of the main text.

Table S3. Succession rules for SP1 forest unit in Pic River Forest.

#	Pre-transition FU	Age of transition	Post-transition FU	Age of post-transition FU	Fraction of area succeeding
1	SP1	135	SP1	125	0.30
2	SP1	155	MW2	35	0.05
3	SP1	155	SF1	35	0.15
4	SP1	155	SP1	35	0.30
5	SP1	155	SP1	135	0.50
6	SP1	205	SP1	35	1.00

Note that ages of transition and post-transition FU in Table S2 refer to the mid-points of the 10-year age classes.

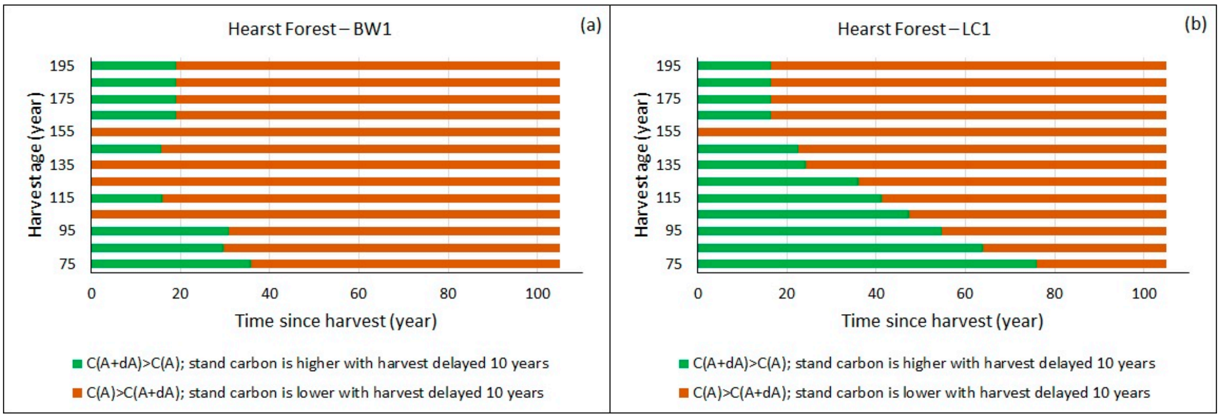
In the above example, there are six successional rules for FU SP1. Let us consider a 100-ha stand classified as SP1. For the first 125 years since the last stand-replacing disturbance the stand follows the yield curve for SP1. Between ages 125 and 135, transition rule #1 takes effect, with 30 hectares of the stand (0.3 of the area) "transitioning" to FU SP1, age class 125 (in this particular case it means that these 30 hectares retain the volume and species composition of a 125-year-old SP1 stand); the remaining 70 ha remain in SP1, with their age increasing to 135 years. These 70 ha undergo successional changes between ages 145 and 155 as specified by four transition rules #2–5: 3.5 ha (= 0.05 x 70 ha) move to the state with volume and species composition corresponding to those of FU MW2 at age 35 (rule #2); 10.5 (= 0.15 x 70 ha) turn into FU SF1 at age 35 (rule #3); 21 ha (= 0.30 x 70 ha) turn into FU SP1 at age 35 (rule #4); and 35 ha (= 0.50 x 70 ha) turn into FU SP1 at age 135 (rule #5).

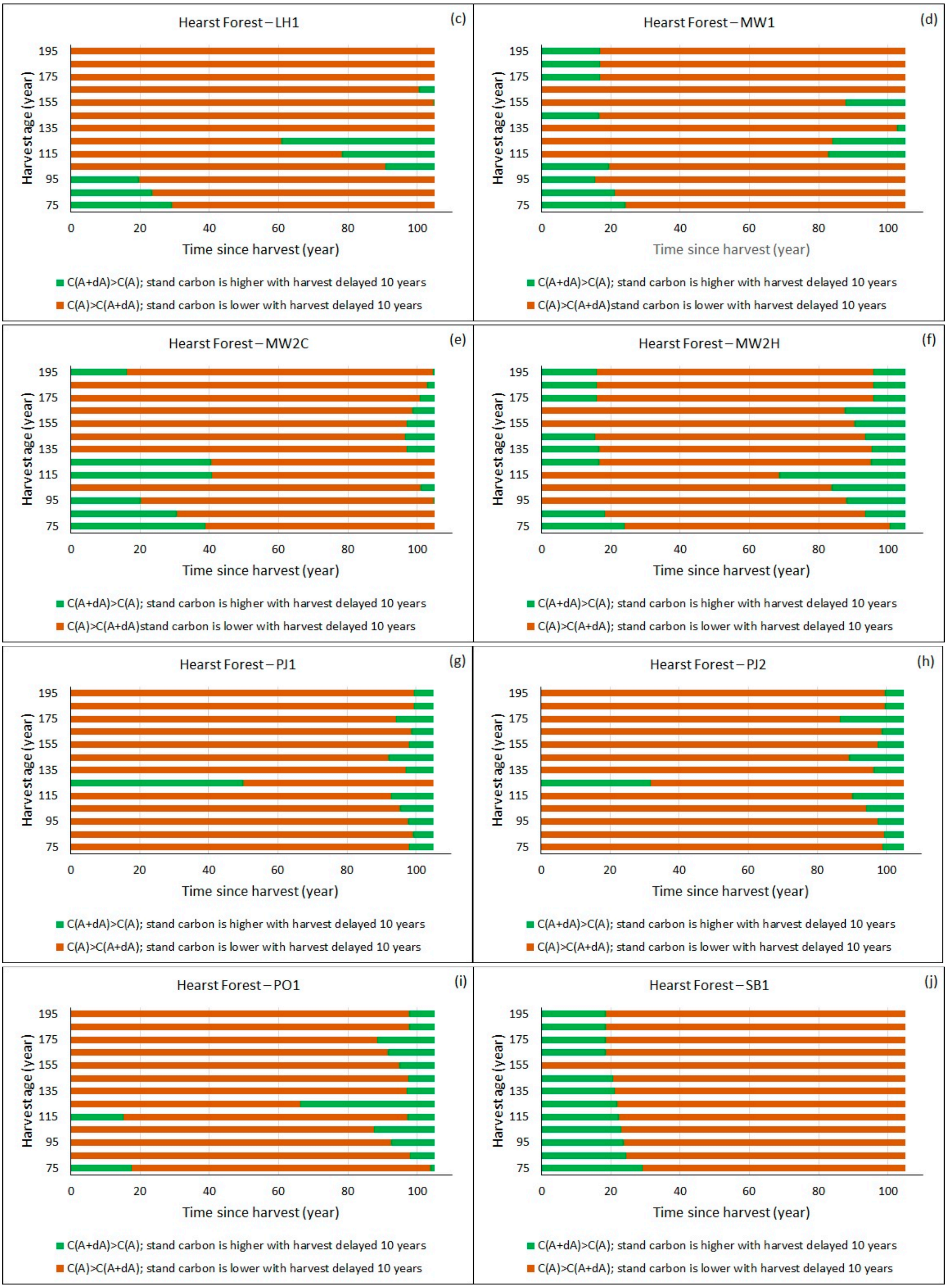
In the above example, rule #6 may appear excessive because by age 155 all 100 ha of the original stand have transitioned to some other FU-age combination. Rule #6 is included to "catch" stands with age greater than or equal to 155 at the beginning of the simulation. This is because succession rules are intended to simulate growth of all forests in a given forest management unit, and can be thought of as applying spatially to all forest stands in a given FU and age: some stands will transition earlier following one rule, others may do it later following other rules but all stands eventually undergo successional transitions to other forest units and ages. The above description of a single stand being partitioned among various FUs in different stages of development is a simplified example to show what happens on average to all stands in FU SP1 in Pic River Forest. This example also helps to illustrate how to estimate volumes for a composite yield curve: area-weighted volumes of individual partitions (defined by their FU and age) are combined to produce an average composite yield curve of a stand originally classified as FU SP1.

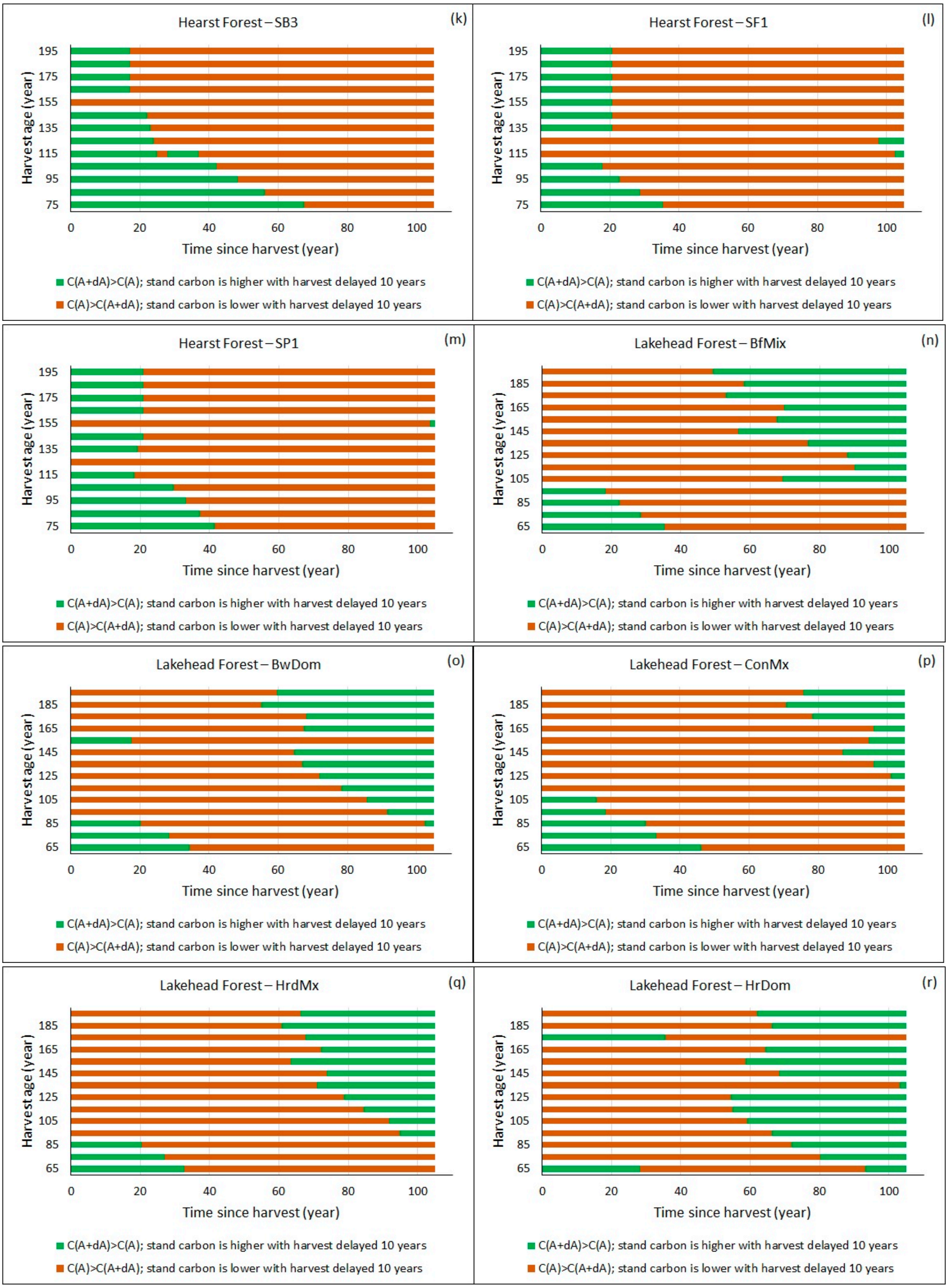
4. Climate change mitigation benefit profiles

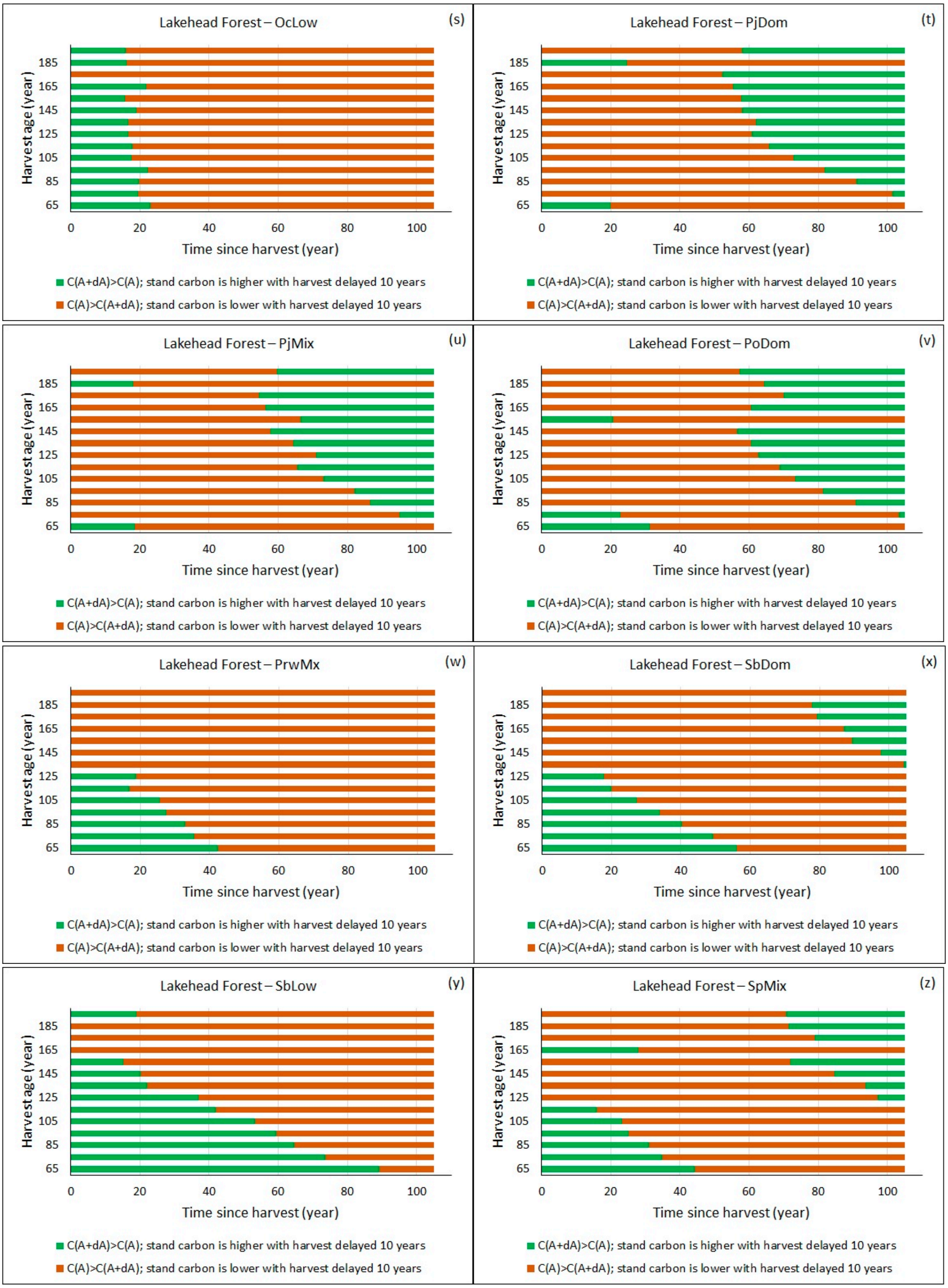
Figure S1 shows climate change mitigation benefit profiles for all 36 FUs in the three FMUs in boreal forests of Ontario. Mitigation benefit profiles are presented in the same order of FUs as in Table S1. The FMU and FU names are indicated in the chart titles.

Figure S1. Climate change mitigation benefit profiles of increasing base harvest age by 10 years for 36 forest units in three forest management units in Ontario's boreal forests.

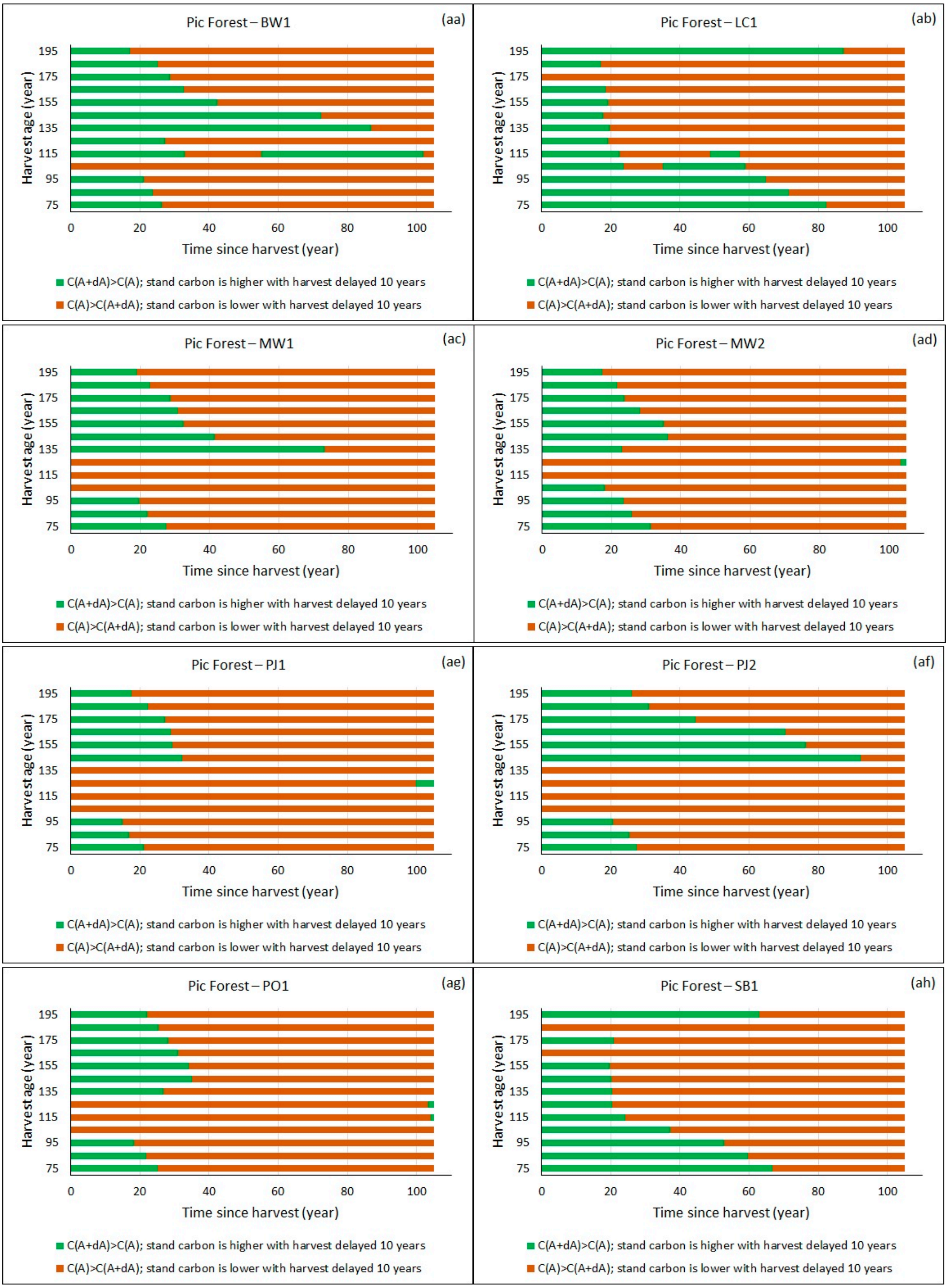



Hearst Forest – LH1
(c)
Harvest age (year)
195
175
155
135
115
95
75
0
20
40
60
80
100
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Hearst Forest – MW1
(d)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA)stand carbon is lower with harvest delayed 10 years
Hearst Forest – MW2C
(e)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA)stand carbon is lower with harvest delayed 10 years
Hearst Forest – MW2H
(f)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Hearst Forest – PJ1
(g)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Hearst Forest – PJ2
(h)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Hearst Forest – PO1
(i)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Hearst Forest – SB1
(j)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years

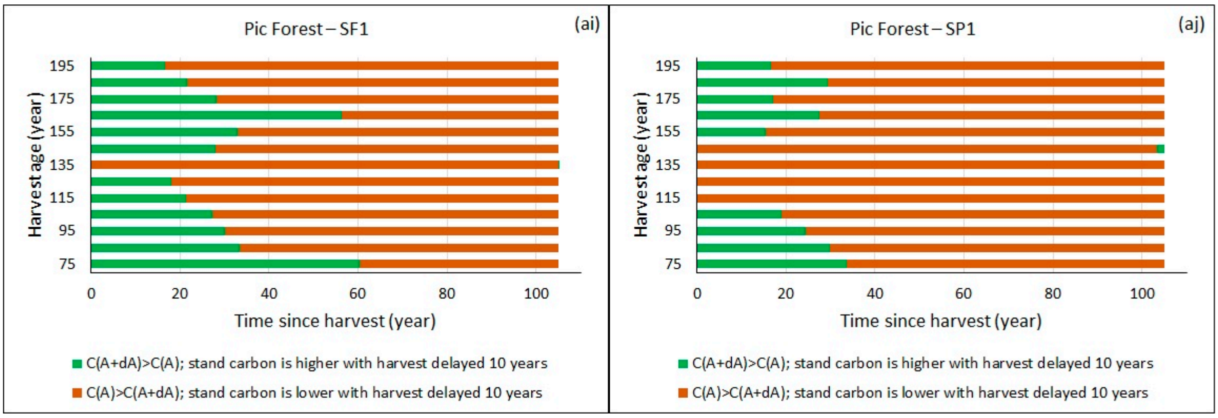

Hearst Forest – SB3
(k)
195
175
155
135
115
95
75
Harvest age (year)
0
20
40
60
80
100
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Hearst Forest – SF1
(l)
195
175
155
135
115
95
75
Harvest age (year)
0
20
40
60
80
100
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Hearst Forest – SP1
(m)
195
175
155
135
115
95
75
Harvest age (year)
0
20
40
60
80
100
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Lakehead Forest – BfMix
(n)
185
165
145
125
105
85
65
Harvest age (year)
0
20
40
60
80
100
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Lakehead Forest – BwDom
(o)
185
165
145
125
105
85
65
Harvest age (year)
0
20
40
60
80
100
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Lakehead Forest – ConMx
(p)
185
165
145
125
105
85
65
Harvest age (year)
0
20
40
60
80
100
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Lakehead Forest – HrdMx
(q)
185
165
145
125
105
85
65
Harvest age (year)
0
20
40
60
80
100
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Lakehead Forest – HrDom
(r)
185
165
145
125
105
85
65
Harvest age (year)
0
20
40
60
80
100
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years



Lakehead Forest – OcLow
(s)
Harvest age (year)
185
165
145
125
105
85
65
0
20
40
60
80
100
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Lakehead Forest – PjDom
(t)
Harvest age (year)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Lakehead Forest – PjMix
(u)
Harvest age (year)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Lakehead Forest – PoDom
(v)
Harvest age (year)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Lakehead Forest – PrwMx
(w)
Harvest age (year)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Lakehead Forest – SbDom
(x)
Harvest age (year)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Lakehead Forest – SbLow
(y)
Harvest age (year)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years
Lakehead Forest – SpMix
(z)
Harvest age (year)
Time since harvest (year)
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years



Pic Forest – BW1
(aa)
Pic Forest – LC1
(ab)
Pic Forest – MW1
(ac)
Pic Forest – MW2
(ad)
Pic Forest – PJ1
(ae)
Pic Forest – PJ2
(af)
Pic Forest – PO1
(ag)
Pic Forest – SB1
(ah)
Harvest age (year)
195
175
155
135
115
95
75
Time since harvest (year)
0
20
40
60
80
100
C(A+dA)>C(A); stand carbon is higher with harvest delayed 10 years
C(A)>C(A+dA); stand carbon is lower with harvest delayed 10 years



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