Recarbonizing global soils – A technical manual of recommended management practices. Volume 5: Forestry, wetlands, urban soils – Practices overview. Chapter 2. Continuous cover forestry and extended rotations.

David Paré, Laurent Augusto

2. Continuous cover forestry and extended rotations

David Paré[1], Laurent Augusto[2]

[1]*Canadian Forest Service, Laurentian Forestry Centre, Québec, Canada*

[2]*INRAE, Bordeaux Sciences Agro, Villenave d'Ornon, France*

1. Description of the practice

Continuous cover forestry (CCF; see the full description in Helliwell and Wilson, 2012) includes many silvicultural systems which all involve continuous and uninterrupted maintenance of forest cover and which avoid clearcutting. It implies forest management that works with the characteristics of the site and with tree species that are well adapted to the location. It respects the processes inherent to the site, rather than imposing artificial uniformity, and will normally involve a mixture of tree species and ages. Management is based on the selection and favouring of individual trees (of all sizes) rather than the creation of areas of uniform tree size and spacing, and record keeping is based on periodic recording of stem diameters on sample areas, rather than by age and area of stands. Stand structure will be permanently irregular, although the process of transformation to an uneven-aged condition might involve temporary even-aged elements, possibly including small-scale clearfells, and group or irregular shelterwoods (Helliwell and Wilson, 2012). CCF could minimize soil disturbance because a larger portion of tree roots are preserved following wood harvesting, and because no soil preparation – such as ploughing– is done. On the other hand, it involves a greater number of soil trampling events as interventions are more frequent. CCF also requires more frequent and more technical interventions of the forest managers. CCF may limit changes to the soil microclimate due to smaller openings comparatively to clear-cutting with potential influence on soil organic matter decomposition. However, positive as well as negative impact of large canopy openings have been observed on organic matter decay rates (Mayer *et al.*, 2020).

2. Range of applicability

Applicability is worldwide, wherever even-aged forestry is practiced. Typically, over the past two centuries, conventional forest management approaches have favored the plantation of even-aged, single-species stands. Interest in alternative management approaches that involve continuous and uninterrupted maintenance of forest cover have greatly increased in many regions, particularly in developed economies (Puettman *et al.,* 2015).

3. Impact on soil organic carbon stocks

Although precise data on SOC changes are scarce, meta-analyses have revealed that clearcut harvesting results in reductions of < 10 percent of the soil C in the entire soil profile with greatest loss of the forest floor (Johnson, 1992; Johnson and Curtis, 2001; Achat *et al.*, 2015). In two meta-analyses of studies in temperate forests, forest harvesting reduced total soil C by an average of 6-8 percent: C storage declined by 22-30 percent in the forest floor, whereas the mineral horizons showed no significant overall change (Nave *et al.*, 2010; Achat *et al.*, 2015). Evidence that CCF reduces soil C losses in comparison to clear cutting is scant. Mayer *et al.* (2020) reported on the following studies: In Norway-spruce-dominated stands in Austria, single-tree-selection management resulted in 11 percent greater soil C stocks in the upper mineral soil compared to conventional even age-class management (Potzelsberger and Hasenauer, 2015). However, short-term losses were observed in shelterwood cuts in Chilean Patagonia (Klein *et al.*, 2008). In an oak-hardwood forest in New England, Warren and Ashton (2014) reported a decrease in the soil C stocks in the mineral soil, but neutral effects in the litter layer following shelterwood harvest. Others have found little or no difference between effects of partial, selection, shelterwood, and clearcut harvesting on soil C stocks (Hoover, 2011; Christophel *et al.*, 2015; Puhlick *et al.*, 2016). When differences in SOC content were observed, they were higher under CCF but of low magnitude (Pötzelsberger and Hasenauer, 2015; Jonard *et al.*, 2017). Similarly, two meta-analyses (Liao *et al.* 2010, 2012) showed a systematic loss of SOC in planted even-aged forests compared to naturally regenerated forests, but this difference in SOC storage could be linked to the fact that the naturally regenerating forests in these studies are partly primary forests, with SOC stocks probably at high level. In summary, information is too fragmentary to attribute any soil C changes with the adoption of CCF in replacement of a traditional even-aged silviculture system (Powers *et al.*, 2011). Local information on the effect of this practice on soil erosion, soil disturbance, as well as on impact on forest composition would be factors to consider due to their potential impact on soil C stocks. It is noteworthy that CCF systems involve light but more frequent interventions that could make changes in the soil C stocks at the whole rotation scale difficult to detect statistically.

4. Other benefits of the practice

4.1 Minimization of threats to soil functions

Table 3. Soil threats

Soil threats	
Soil erosion	On sites sensitive to erosion, maintaining a forest canopy as well as tree root systems could prevent erosion.
Nutrient imbalance and cycles	Especially if the adoption of this practice promotes mixed species stands.
Soil acidification	The absence of clearcut in CCF might slightly reduce the losses of cations induced by water leaching enhanced by clearcuts in sites prone to such losses (i.e. mainly soils with a high drainage regime but with a low buffering capacity of pH).
Soil biodiversity loss	In general, positive impact on biodiversity noting that some forest species need open canopy conditions or high disturbance levels. But the latter (i.e. ruderal species) are usually not a concern for biodiversity (Puetman *et al.* 2015).
Soil compaction	In general, the maintenance of the tree root systems might increase the resistance of soils to compaction. However, the current knowledge about this possible effect is scarce.
Soil water management	CCF enables better regulation of the water fluxes at the watershed scale.

4.2 Increases in production (e.g. food/fuel/feed/timber)

Some studies indicate equivalent or lower productivity (-20 percent) rates in CCF systems (reviewed by Lundmark *et al.*, 2016).

4.3 Mitigation of and adaptation to climate change

There is no strong evidence that soil C stock differs between CCF and clear-cut systems. Local situations should be examined carefully. In a broader perspective, mitigation benefits from the outflow of forest products that substitute the use of materials generating greater GHG emissions in addition to those related to the changes in C stocks, both in forest ecosystems and in wood products need to be considered. Lundmark *et al.* (2016) indicated that for Norway spruce in Sweden, biomass growth and yield is more important than the choice of silvicultural system per se for generating long term climate mitigation benefits associated with CO_2 emissions and C stock changes. In Canada, Paradis, Thiffault and Achim (2018) indicated that forest management systems that produce trees of greater size should increase the proportion of long-lived wood products, suggesting that the quality of the timber produced also has implication on GHG mitigation.

There is evidence that multi-species and multi-cohorts forest stands are more resilient to climate-change and to other threats, especially in the long-term (reviewed by Puettmann *et al.*, 2015). However, unexpected mortality of residual trees may occur with CCF, especially when foresters have little experience with such practice (Puettmann *et al.*, 2015).

Due to climate change and associated effects, it is envisaged to reduce these rotation durations to mitigate the risks associated with storms, fires or pathogen attacks (Roux *et al.*, 2017). This amounts to shifting from carbon sequestration in the ecosystem to carbon storage in products and increasing the share of substitution (Fortin *et al.*, 2012). From an ecosystem perspective, shortening rotations can have an impact on soil fertility and SOC with a general decreasing trend (Achat *et al.*, 2018). As the stand is renewed more often over the same period of time, biomass and nutrient exports are greater and the effects of soil preparation during forest soil regeneration on SOC are also amplified. Thus, the longer the duration of rotation, the more likely it is that SOC will increase, although the effect of very long rotations (*i.e.* several centuries) remains poorly known with variable results depending on the studies (Ji *et al.*, 2017; Leuschner *et al.*, 2014; Zhou *et al.*, 2006). Thus, simultaneously, the risk of climate change-related hazards increases (and may contribute to the reduction of the SOC stock in trees) with the length of the rotation , whereas the shorter the rotation, the greater the SOC losses related to forest management may be (Seely, Welham and Blanco, 2010). However, to date, there are no studies where forest stands are monitored longitudinally (not in chronosequence) over a longer timeframe and have experienced intensive silviculture (several short revolutions) on the one hand or extensive silviculture on the other (long rotation over the same time period). Only model-based studies can address the effect of the length of rotation on SOC (Johnson, Scatena and Pan, 2010; Wang *et al.*, 2013; Seely, Welham and Kimmins, 2002; Achat *et al.*, 2018). Numerical simulations are generally concordant and suggest a decrease in SOC stocks with a shortening of rotations (e.g. -15 to -20 percent after 360 years; Johnson *et al.*, 2010).

4.4 Socio-economic benefits

Continuous-cover forestry could generate more uniform cash flows (Puettmann *et al.* 2015); successful natural regeneration avoids the cost of plantation establishment.

Improvement of landscape visual quality and enhanced recreational opportunities (Puettmann *et al.* 2015).

5. Potential drawbacks to the practice

5.1 Decreases in production (e.g. food/fuel/feed/timber)

Some studies indicate equivalent or lower productivity (-20 percent) rates in CCF systems (reviewed in Lundmark *et al.,* 2016).

6. Recommendations before implementation of the practice

The greatest risk is the enhanced mortality of residual trees due to damages to roots and stems during operation or to greater exposure of residual trees to wind, drought or insects. It is advisable to start at small scale with a good knowledge of species autecology and with clear stand-density management goals.

7. Potential barriers to adoption

Table 4. Potential barriers to adoption

Barrier	YES/NO	
Biophysical	Yes	Implementation is not always easy depending on the current forest composition and structure, may need several steps.
Economic	Yes	Yields are less certain in regions with no tradition of CCF.

Photo of the practice

Photo 2. A mature stand of Douglas fir managed on CCF principles with a developing understorey of mixed conifers, including Douglas fir, western hemlock, western red cedar and grand fir | Coombs Wood, Cumbria, United Kingdom of Great Britain and Northern Ireland |

References

Achat, D.L., Fortin, M., Landmann, G., Ringeval, B. & Augusto, L. 2015. Forest soil carbon is threatened by intensive biomass harvesting. *Scientific Reports,* 5: 15 991. https://doi.org/10.1038/srep15991

Achat, D.L., Martel, S., Picart, D., Moisy, C., Augusto, L., Bakker, M.R. & Loustau, D. 2018. Modelling the nutrient cost of biomass harvesting under different silvicultural and climate scenarios in production forests. *Forest Ecology and Management*, 429: 642-653. http://dx.doi.org/10.1016/j.foreco.2018.06.047

Christophel, D., Höllerl, S., Prietzel, J. & Steffens, M. 2015. Long-term development of soil organic carbon and nitrogen stocks after shelterwood- and clear-cutting in a mountain forest in the Bavarian Limestone Alps. *European Journal of Forest Research,* 134: 623–640. https://doi.org/10.1007/s10342-015-0877-z

Fortin, M., Ningre, F., Robert, N. & Mothe, F. 2012. Quantifying the impact of forest management on the carbon balance of the forest-wood product chain: A case study applied to even-aged oak stands in France. *Forest Ecology and Management*, 279: 176-188. http://dx.doi.org/10.1016/j.foreco.2012.05.031

Helliwell, R. & Wilson, E.R. 2012. Continuous cover forestry in Britain: challenges and opportunities. *Quarterly Journal of Forestry,* 106(3): 214-224.

Ji, Y.H., Guo, K., Fang, S.B., Xu, X.N., Wang, Z.G. & Wang, S.D. 2017. Long-term growth of temperate broadleaved forests no longer benefits soil C accumulation. *Scientific Reports*, 7. http://dx.doi.org/10.1038/srep42328

Johnson, D.W. 1992. Effects of forest management on soil organic carbon. *Water Air and Soil Pollution,* 64: 83-120.

Johnson, K., Scatena, F.N. & Pan, Y.D., 2010. Short- and long-term responses of total soil organic carbon to harvesting in a northern hardwood forest. *Forest Ecology and Management*, 259 (7): 1262-1267. http://dx.doi.org/10.1016/j.foreco.2009.06.049

Jonard, M., Nicolas, M., Coomes, D.A., Caignet, I., Saenger, A. & Ponette, Q. 2017. Forest soils in France are sequestering substantial amounts of carbon. *Science of the Total Environment*, 574: 616-628. http://dx.doi.org/10.1016/j.scitotenv.2016.09.028

Leuschner, C., Wulf, M., Bauchler, P. & Hertel, D. 2014. Forest continuity as a key determinant of soil carbon and nutrient storage in beech forests on sandy soils in northern Germany. *Ecosystems*, 17(3): 497-511. http://dx.doi.org/10.1007/s10021-013-9738-0

Liao, C.Z., Luo, Y.Q., Fang, C.M., Chen, J.K. & Li, B. 2012. The effects of plantation practice on soil properties based on the comparison between natural and planted forests: a meta-analysis. *Global Ecology and Biogeography*, 21(3): 318-327. http://dx.doi.org/10.1111/j.1466-8238.2011.00690.x

Liao, C.Z., Luo, Y.Q., Fang, C.M. & Li, B. 2010. Ecosystem carbon stock influenced by plantation practice: implications for planting forests as a measure of climate change mitigation. *Plos One*, 5(5). http://dx.doi.org/10.1371/journal.pone.0010867

Lundmark, T., Bergh, J., Nordin, A., Fahlvik, N. & Poudel, B.C. 2016. Comparison of carbon balances between continuous-cover and clearcut forestry in Sweden. *Ambio,* 45: 203–213. https://doi.org/10.1007/s13280-015-0756-3

Mayer, M., Prescott, C.E., Abaker, W.E.A., Augusto, L., Cécillon, L., Ferreira, G.W.D., James, J., Jandl, R., Katzensteiner, K., Laclau, J.-P., Laganière, J., Nouvellon, Y., Paré, D., Stanturf, J.A., Vanguelova, E.I. & Vesterdal, L. 2020. Tamm review: influence of forest management activities on soil organic carbon stocks: a knowledge synthesis. *Forest Ecology and Management,* 466: 118127. https://doi.org/10.1016/j.foreco.2020.118127

Nave, L.E., Vance, E.D., Swanston, C.W. & Curtis, P.S. 2010. Harvest impacts on soil carbon storage in temperate forests. *Forest Ecology and Management,* 259: 857–866. https://doi.org/10.1016/j.foreco.2009.12.009

Paradis, L., Thiffault, E. & Achim, A. 2019. Comparison of carbon balance and climate change mitigation potential of forest management strategies in the boreal forest of Quebec (Canada). *Forestry,* 92: 264–277. https://doi.org/10.1093/forestry/cpz004

Pötzelsberger, E. & Hasenauer, H. 2015. Soil change after 50 years of converting Norway spruce dominated age class forests into single tree selection forests. *Forest Ecology and Management*, 338: 176-182. https://doi.org/10.1016/j.foreco.2014.11.026

Powers, M., Kolka, R., Palik, B., McDonald, R. & Jurgensen, M. 2011. Long-term management impacts on carbon storage in Lake States forests. *Forest Ecology and Management*, 262(3): 424-431. http://dx.doi.org/10.1016/j.foreco.2011.04.008

Puettmann, K.J., Wilson, S. McG, Baker, S.C. Donoso, P.J., Drössler, L., Amente, G., Harvey, B.D., Knoke, T., Lu, Y., Nocentini, S., Putz, F.E., Yoshida, T. & Bauhus, J. 2015. Silvicultural alternatives to conventional even-aged forest management - what limits global adoption? *Forest Ecosystems,* 2. https://doi.org/10.1186/s40663-015-0031-x

Roux, A., Dhôte, J.-F. (Coordinators), Achat, D., Bastick, C., Colin, A., Bailly, A., Bastien, J.-C., Berthelot, A., Bréda, N., Caurla, S., Carnus, J.-M., Gardiner, B., Jactel, H., Leban, J.-M., Lobianco, A., Loustau, D., Meredieu, C., Marçais, B., Martel, S., Moisy, C., Pâques, L., Picart-Deshors, D., Rigolot, E., Saint-André, L. & Schmitt, B. 2017. *Quel rôle pour les forêts et la filière forêt-bois françaises dans l'atténuation du changement climatique ? Une étude des freins et leviers forestiers à l'horizon 2050* (Doctoral dissertation, Institut National de la Recherche Agronomique (INRA); Institut Géographique National (IGN)).

Seely, B., Welham, C. & Blanco, J.A., 2010. Towards the application of soil organic matter as an indicator of forest ecosystem productivity: Deriving thresholds, developing monitoring systems, and evaluating practices. *Ecological Indicators*, 10(5): 999-1008. http://dx.doi.org/10.1016/j.ecolind.2010.02.008

Seely, B., Welham, C. & Kimmins, H., 2002. Carbon sequestration in a boreal forest ecosystem: results from the ecosystem simulation model, FORECAST. *Forest Ecology and Management*, 169 (1-2): 123-135. http://dx.doi.org/10.1016/s0378-1127(02)00303-1

Wang, W.F., Wei, X.H., Liao, W.M., Blanco, J.A., Liu, Y.Q., Liu, S.R., Liu, G.H., Zhang, L., Guo, X.M. & Guo, S.M. 2013. Evaluation of the effects of forest management strategies on carbon sequestration in evergreen broad-leaved (Phoebe bournei) plantation forests using FORECAST ecosystem model. *Forest Ecology and Management*, 300: 21-32. http://dx.doi.org/10.1016/j.foreco.2012.06.044

Zhou, G.Y., Liu, S.G., Li, Z., Zhang, D.Q., Tang, X.L., Zhou, C.Y., Yan, J.H. & Mo, J.M., 2006. Old-growth forests can accumulate carbon in soils. *Science*, 314(5804): 1417-1417. http://dx.doi.org/10.1126/science.1130168