Adaptive Silviculture

in the Context of a Changing Climate

Guidebook

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Forword

This Guidebook on Adaptive silviculture in the context of a changing climate is a projected conducted by the Northern Hardwoods Research Institute (NHRI) and the University of New Brunswick (UNB) under the funding from the Natural Resources Canada's Climate Change Adaptation Program.

This version is preliminary, and an update will be provided in spring 2023.

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1. INTRODUCTION

Climate change has been underway for several decades now and its impact of our forests has been occurring in several parts of the world including our regions. Given the magnitude of climate change and its progression it is important to consider these factors during forest management decisions. Hagerman and Pelai (2018) recently published a review on recommendations to adapt forests to climate change. They conclude that most studies suggest maintaining the existing ecological patterns and processes while others propose a transition to resilient forests through active interventions (Messier et al. 2019). In addition, most recommendations are based on general and non-specific principles. Although more specific suggestions can be found in the literature, they are tailored to species and climatic conditions found in the study region of the case study example. The present document aims to present a guideline for adapting New Brunswick forests to climate change.

2. CLIMATIC AND FOREST CHANGES

We are gaining a good perspective on the impacts of climate change on our forests. A lot of research and a several literature reviews have been done on that subject. Taking Taylor's publication in 2017 as an example, which presents the impacts of the climate change, we see that depending on which RCP scenario we want to look at, there are predictions of short-, medium- and long-term impacts of the changing climate on forest species (Figure 1). Some species are going to be positively impacted by climate change or by the increase in temperature and increase in precipitation. In the graph, the three adjacent bars represent the short-term, mid-term and long-term departure from the baseline. We clearly see that hardwood species like American Beech, Red Maple, Red Oak and White Ash will benefit and will be more prominent than other species in light of changing climate in the next 80 years. There are other species like Sugar Maple, Trembling Aspen and White Birch where the trend is reverse, and their health and distribution will be affected negatively. On the other hand, Yellow Birch is anticipated to not change significantly.

For the prediction of softwood composition in the next 80 years, it is anticipated that Eastern Cedar, Eastern Hemlock and White Pine will not be affected significantly. But the other softwood species are going to see a decrease in their proportions due to climate change.

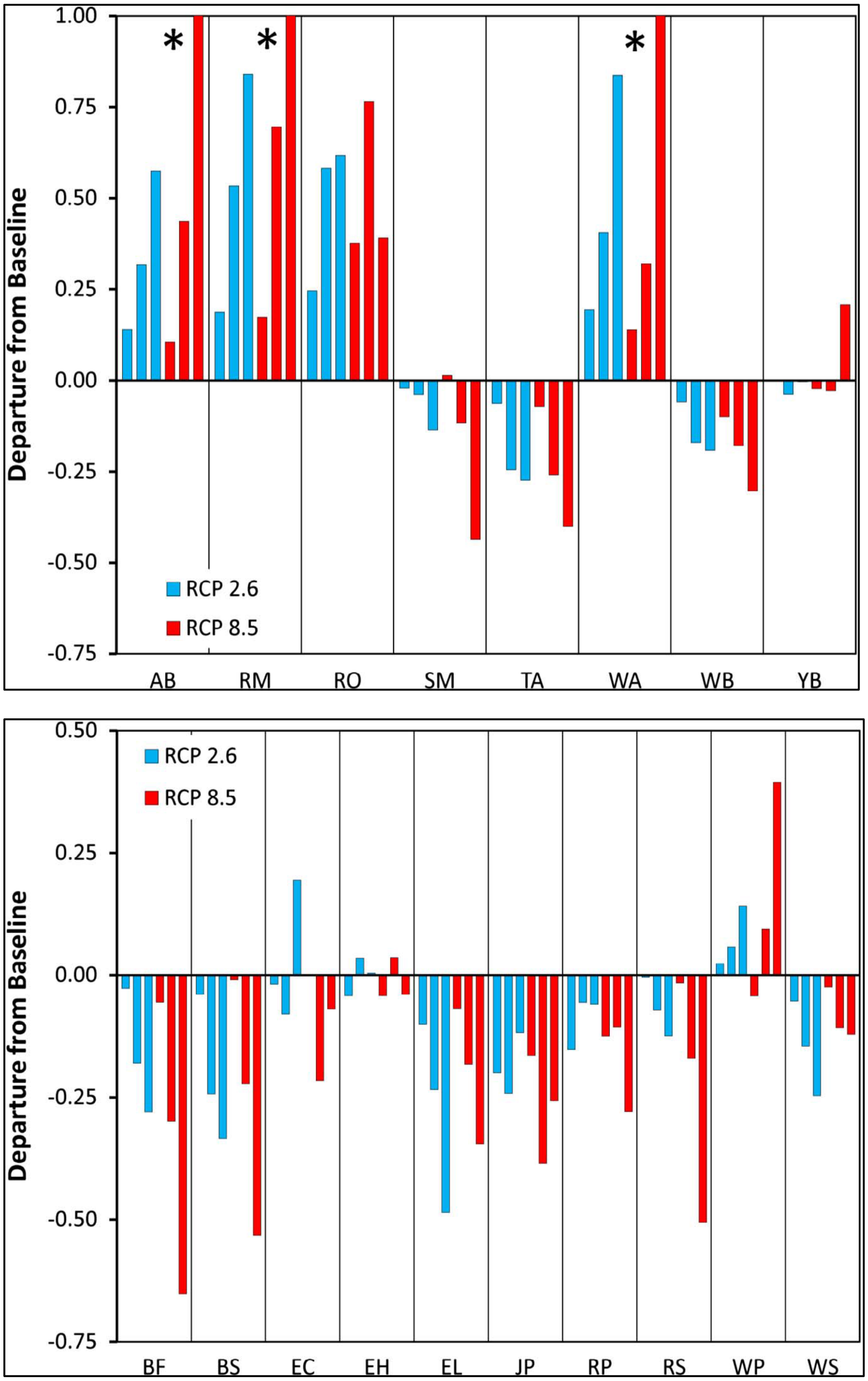


Figure 1. Species composition impacted by climate change (Taylor et al. 2017)

If we express this in terms of Current Annual Increment (CAI), the trend shows that boreal species will tend to decrease in productivity while more temperate species will increase in current annual increment (Taylor et al. 2007)(Figure 2). This summarizes well the direct impacts on climate change on the productivity of some groups of species. In New Brunswick, with the current blend of softwood and hardwood species, the net trajectory of all species compounded results in a slightly downward trend in productivity.

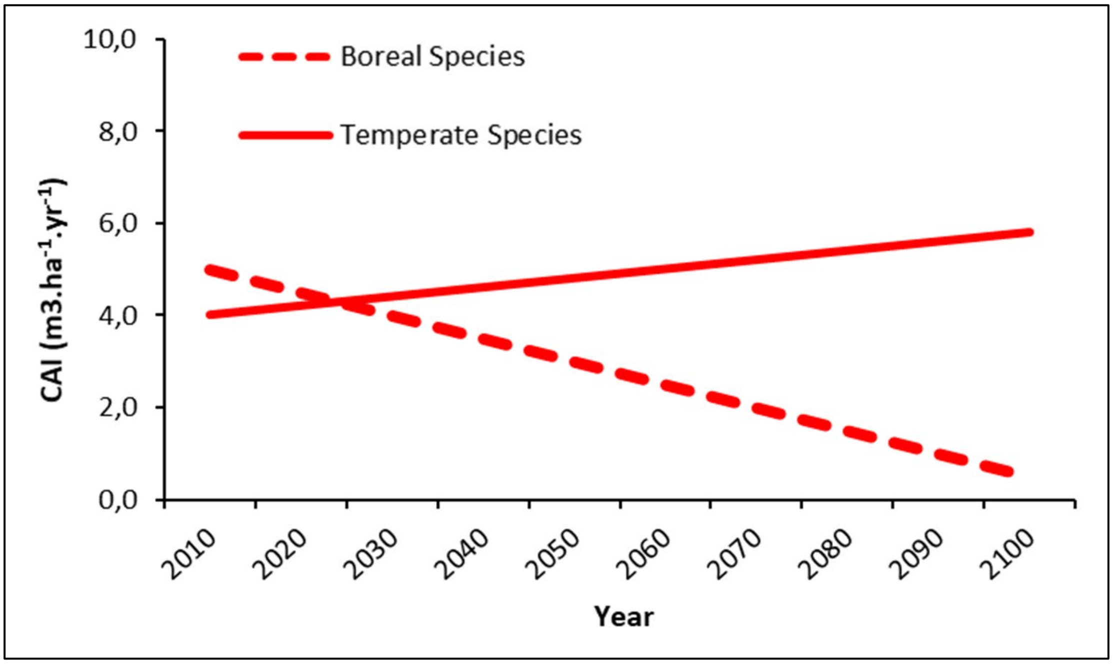


Figure 2. Productivity in terms of CAI on species (Taylor et al. 2017)

There are obvious potential risks for species of commercial importance (Figure 3). As far as we know, Balsam Fir, Black and Red Spruce, Sugar Maple, Aspen and White Birch will be the most impacted. And then there are a few odd things, for example, White Ash is forecasted to do better but there is a catch due to the emerald ash borer. Butternut is a similar case with the impact of canker. But the thing to watch for is the dramatic increase forecasted for American Beech and Red Maple. Those are called interfering species because they interfere with Sugar Maple and Yellow Birch and compete for the same ecological niche.

But climate change also offers some opportunities. Red Oak is forecasted to do better as well as White Pine. Yellow Birch is forecasted to do slightly better, so in a way, what we lose in Sugar Maple in that niche may be taken by Yellow Birch, White Spruce, Eastern Cedar and Eastern Hemlock.

It is important to realize that the forecasted scenarios in species occurrence is the result of impacts on forests in the absence of adaptive silviculture. So, in other words, if we do not change anything in our silviculture practices, here is what will happen.

POTENTIAL RISKS

Reduction of today's prime species

- Balsam Fir
- Black and Red Spruce
- Sugar Maple
- Aspen and White Birch

Adding insult to injury

- White Ash (EAB)
- Butternut (canker)

Increase in « interfering species »

- American Beech
- Red Maple

POTENTIAL OPPORTUNITIES

Opportunities with some species

- Red Oak
- White Pine

Opportunities with « safer » species

- Yellow Birch ?
- White Spruce
- Eastern Cedar
- Eastern Hemlock

Figure 3. Summary of predictions in the absence of adaptive silviculture

We are facing a challenge here. To be practical, let's make some calculations with simplistic and probably inaccurate math but still useful to illustrate a point. For example, from Taylor's predictions, in 80 years from now (in 2100), in New Brunswick the climate could be the equivalent of the climate today around Philadelphia or Northern Virginia. This is approximately 1200 km south of us, so the climate is changing at 15 kms per year. Trees generally expand their range at a rate of approximately 100 to 200 meters per year. So, it would take a tree from that zone, like Loblolly Pine (Figure 4) 6000 years to get here on their own if their migration is not interfered by pests, pathogens, and abiotic factors. That means that it is not realistic to start adapting today by favoring species that are doing well way down in the south from us because of this issue. The migration of trees will be slower than the change of habitat itself.

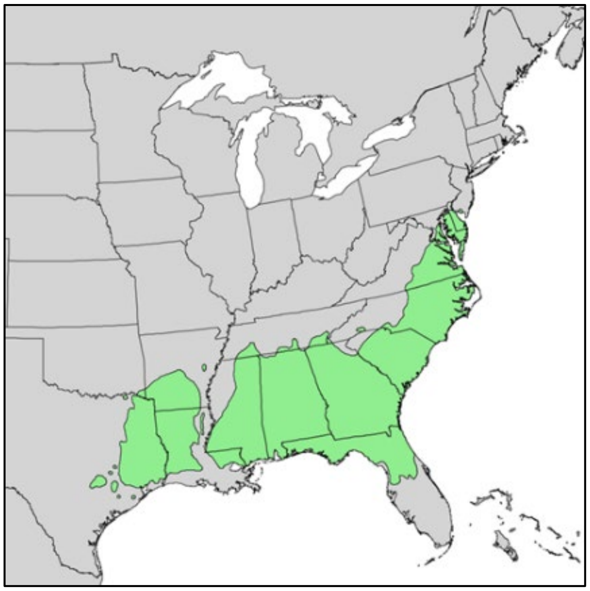


Figure 4. Loblolly Pine Current Range (Source: Elbert L. Little, Jr./U.S. Department of Agriculture, Forest Service/Wikimedia Commons)

The impacts of climate change on New Brunswick's forests can be summarized on the basis of vulnerability assessment. Under the high greenhouse gas emission scenario (RCP 8.5), climatic conditions have been projected and will affect forests through a series of factors such as forest fires, pests, diseases, invasive species, extreme climatic events and predicted potential species compositions. The forest vulnerability has been assessed at the ecoregion level. The projected vulnerability level is divided into eight classes and identified with a different color.

Table 1. Summary of the assessment of vulnerability using the predicted potential species composition, eastern spruce budworm, brown spruce longhorn beetle and fire. Vulnerability levels are compared to those observed in the recent past (1950 to 2010).

Species	1950–2005 to 2036–2065					2036–2065 to 2066–2100			
	Potential composition	SBW[1]	BSLB[3]	Fire		Potential composition	SBW[4]	BSLB	Fire
Balsam Fir	Highlands/ Uplands[2]	Highlands/ Uplands				Highlands/ Uplands	Highlands/ Uplands		
	Lowlands	Lowlands				Lowlands	Lowlands		
Black Spruce	Highlands/ Uplands	Highlands/ Uplands	Highlands/ Uplands			Highlands/ Uplands	Highlands/ Uplands	Highlands/ Uplands	
	Lowlands	Lowlands	Lowlands			Lowlands	Lowlands	Lowlands	
Eastern white cedar									
Jack Pine	Highlands/ Uplands					Highlands/ Uplands			
	Lowlands					Lowlands			
Trembling aspen	Highlands/ Uplands					Highlands/ Uplands			

Species	1950–2005 to 2036–2065					2036–2065 to 2066–2100			
	Potential composition	SBW[1]	BSLB[3]	Fire		Potential composition	SBW[4]	BSLB	Fire
	Uplands Maritimes					Uplands Maritimes			
	Lowlands					Lowlands			
White Birch	Highlands/ Uplands					Highlands/ Uplands			
	Lowlands					Lowlands			
White Spruce	Highlands	Highlands/ Uplands	Highlands			Highlands	Highlands/ Uplands	Highlands	
	Uplands		Uplands			Uplands		Uplands	
	Lowlands	Lowlands	Lowlands			Lowlands	Lowlands	Lowlands	
Red Maple	Highlands/ Uplands					Highlands/ Uplands			
	Lowlands					Lowlands			
Red Oak	Highlands/ Uplands					Highlands/ Uplands			
	Lowlands					Lowlands			
Red Spruce	Highlands/ Uplands	Highlands/ Uplands	Highlands/ Uplands			Highlands/ Uplands	Highlands/ Uplands	Highlands/ Uplands	
	Northern Lowlands		Northern Lowlands			Northern Lowlands		Northern Lowlands	
	Southern Lowlands	Lowlands	Southern Lowlands			Southern Lowlands	Lowlands	Southern Lowlands	
	Maritimes		Maritimes			Maritimes		Maritimes	
Sugar Maple	Highlands					Highlands			
	Uplands					Uplands			
	Lowlands					Lowlands			
White Pine	Highlands					Highlands			
	Uplands					Uplands			
	Eastern Lowlands					Eastern Lowlands			
	Other Lowlands					Other Lowlands			
Yellow Birch	Highlands					Highlands			
	Uplands					Uplands			
	Eastern Lowlands					Eastern Lowlands			
	Other Lowlands					Other Lowlands			

Notes:

1 SBW: eastern spruce budworm

2 The terms Highlands, Uplands and Lowlands refer to the ecoregions of Zelazny (2007). The Grand Lake ecoregion was integrated into the Lowland region. A belt next to the Bay of Fundy is sometimes identified as Maritimes.

3 BSLB: brown spruce longhorn beetle

4 Assessment based on the assumption that changes in silvicultural practices since the 2020s lead to a lower susceptibility of host species (e.g., more mixed stands).

Legend on vulnerability levels

Very Low	
Much Lower	
Lower	

Similar
Higher
Much Higher
Very High
Extreme

3. ADAPTIVE SILVICULTURE

The concept of adaptive silviculture is the answer to be able to face the challenge before us. There are two elements in the adaptive silviculture (Figure 5). The first element is that adaptive part. So, if you look at a problem, you put your objectives forward and you look at your alternatives. You pick one or a few and you implement them. But most importantly, you set the stage for evaluating those alternatives and then changing them once you realize that the trajectory may have changed. The other element is silviculture. It is the art of manipulating and managing forest stands to achieve objectives. The approach to take is to stage objectives for forest up front and frame the silviculture treatments in a broader structure, right down to the silviculture systems.

> The concept of adaptive silviculture
>
> ADAPTIVE: to manage under uncertainty by making hypotheses, implementing activities, trying alternatives, setting the stage to evaluate results, and adjusting if/when needed.
>
> SILVICULTURE: the art of managing forests to achieve landowner objectives by conducting treatments that are part of a regime that is imbedded in a particular framework.

Figure 5. The concept of adaptive silviculture

Adapting to climate change for our forests is not a discipline by itself. It is all about silviculture. what we do, what actions we take on forests to achieve desired outcomes, it is all based under a framework of silviculture systems and on a very strong foundation in regimes. We need to go back to basics. The fact that the climate is changing is just one variable that we throw in the mix. It represents one more dimension we must consider. And the other important aspect, as mentioned earlier, is the adaptive management. So, because of that if we embrace the concept of adaptive management, we can start tomorrow. We do not have to wait for all the uncertainty to be gone. We can continue managing, we can continue what er are doing, but set it up so we can learn and change quickly if we must.

In New Brunswick, it seems that foresters do not often talk about silviculture regimes. We are too quick to talk about silvicultural treatments. For example, people will say that they are doing an overstory removal. But an overstory removal is the last treatment of a shelterwood system. Are we talking about the same thing? So, the concept of regimes (Figure 6), which is a series of treatments on a timeline become very important as we decide what is it we can do to adapt our forests to a changing climate.

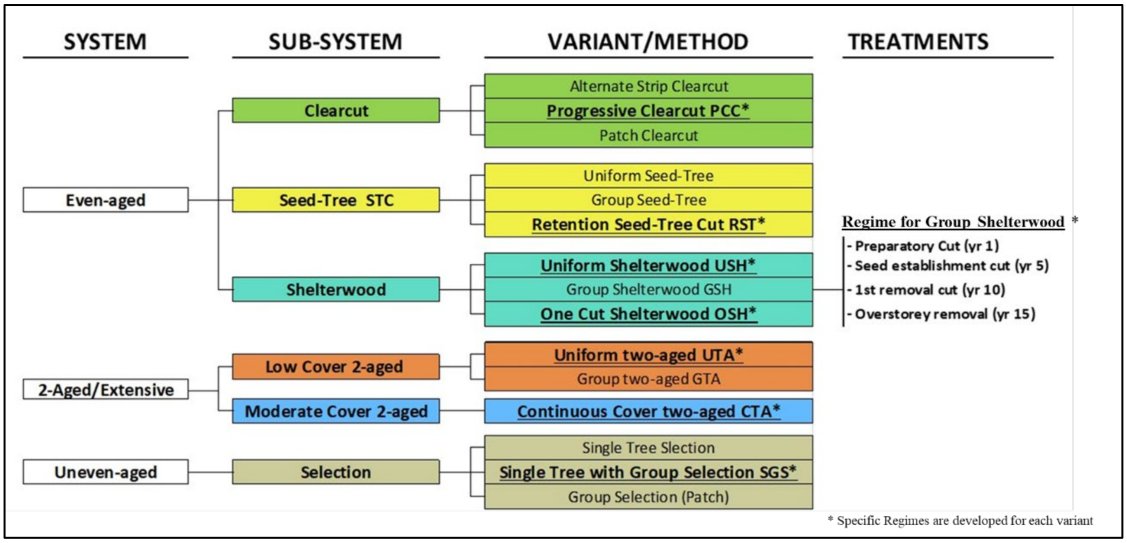


Figure 6. Hierarchy of NHRI Silviculture Framework.

For example, three variants of a shelterwood sub-system can be applied through different regimes (Lessard et al. 2013) (Figure 7). The series of planned treatments along the timeline will be different and specific to each variant. A regime offers many opportunities to adjust the resulting stands. Thinking in terms of regimes is thinking of silviculture as dynamic and a continuum of activities over times.

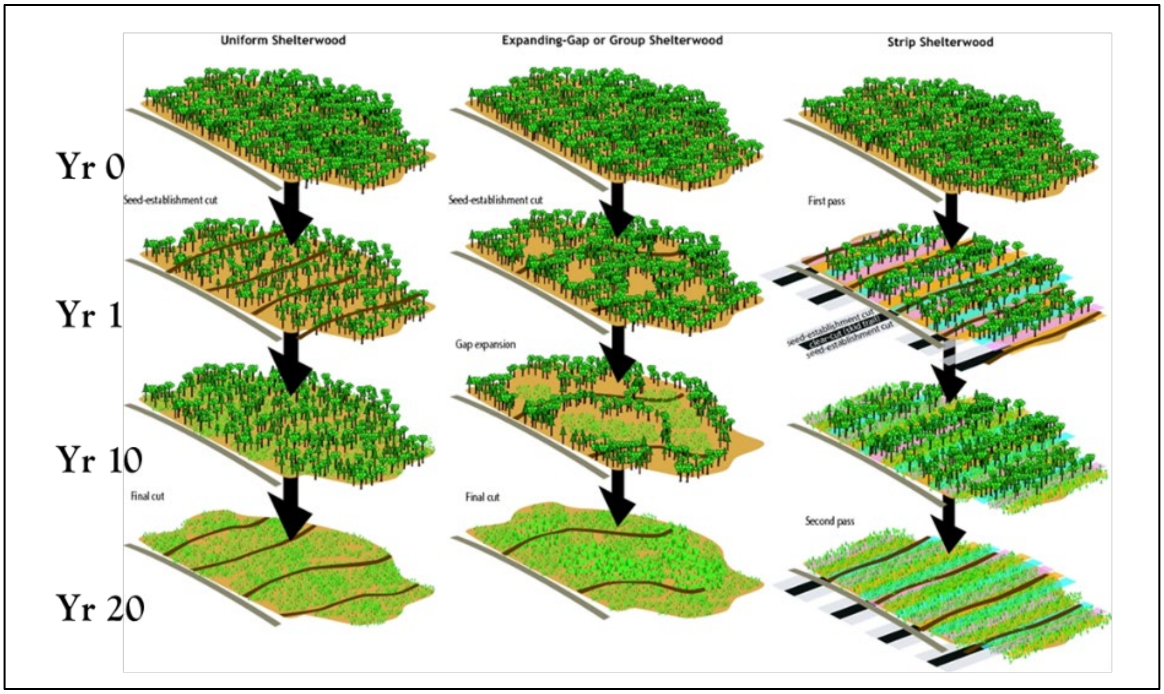


Figure 7. Three Shelterwood Patterns Uniform, Group and Strip (Adapted from Lessard et al. 2013).

4. SEVEN IMPORTANT SILVICULTURE CONCEPTS

It is important to go back and to understand some silvicultural concepts. There are seven important silvicultural concepts that summarizes the basic elements to consider.

Concept no. 1. Tres of different species have different monetary values. Be aware of the great value difference from one species to another. Value is the result of the product mix of an assortment of trees and their respective product value. For example, Red Maple and American Beech yield only 5 – 10% sawlog and the value of lumber is half that of Sugar Maple and Yellow Birch that yield 20-25% sawlogs. In combination, this represents a 4-5-fold difference in value. Yellow Birch and Sugar Maple value is approximately 400$/1000 FBM higher than White Ash and Red Oak (Figure 8).

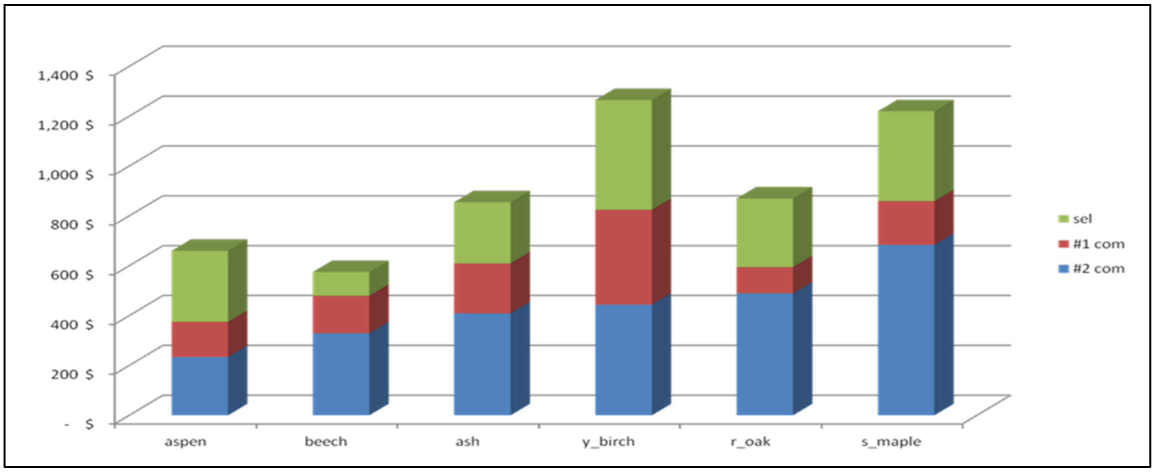


Figure 8. Relative value of selected hardwood species represented as green lumber prices for Northeast (US$/1000 FBM).

Concept no.2. Tree size and form have a direct impact on value and growth rate. Larger trees, to a point, tend to have higher proportion of high-grade products. But as a tree ages it loses vigour and value. Trees with a diameter of more than 40 cm add more discoloured wood volume than clear wood volume, stem quality starts to decline, sawlog recovery diminishes and timber value declines (Figure 9).

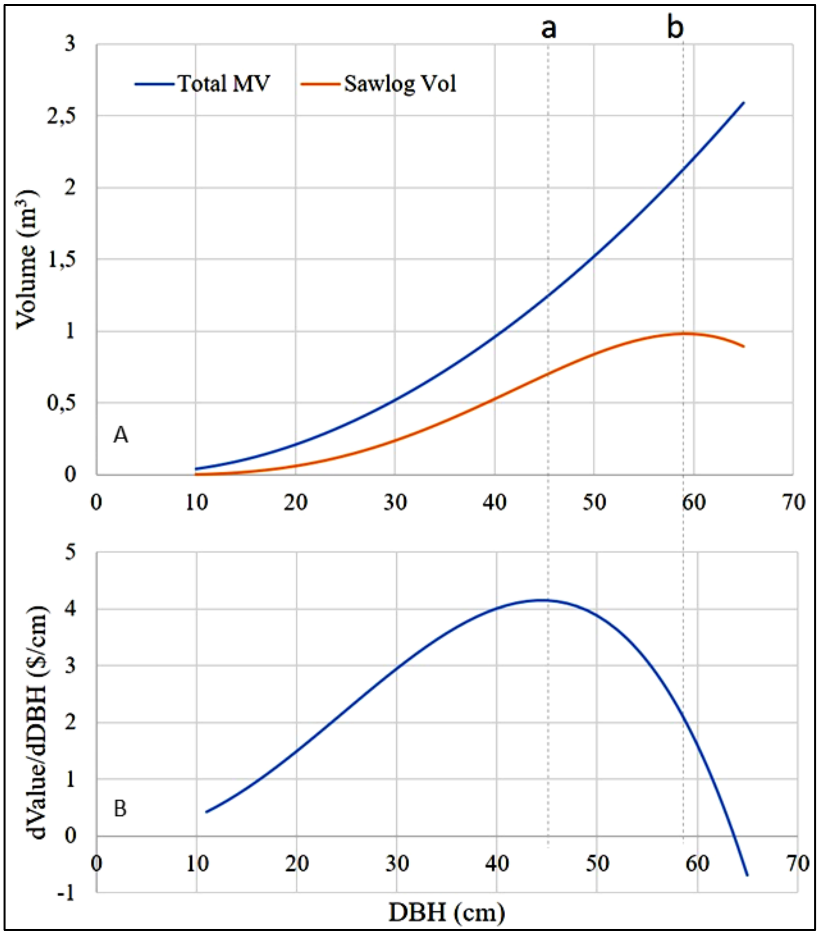


Figure 9. Tree size impacts value and growth rate.

Tree form has a direct impact of product recovery and value. Trees that have an acceptable form and poor form have a lower sawlog ratio that good form trees. Accordingly, the value will be increased in trees with good form tree with no sweep and no fork for example (Figure 10).

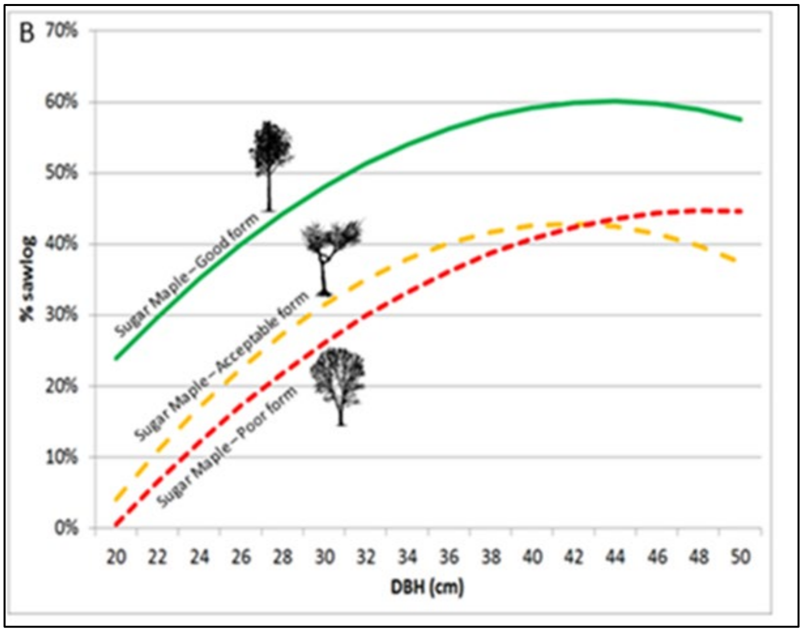


Figure 10. Effect of tree form on the product recovery.

Concept no.3. Competition also impacts stand and tree growth. There is very strong evidence of a narrow range of residual basal area where growth of residual crop trees is optimal (Figure 11). In mixed and hardwood stands in our region, basal area growth can reach a high of 0.8 m2/ha/year. The ideal window for optimal stand growth is between 14 and 18 m2/ha. Leaving more basal area after treatment will cost in growth. Leaving not enough will deplete the growing stock and encourage the establishment of intolerant and pioneer species. Controlling the harvest intensity with the percent basal area removed is important in the recruitment of desired species.

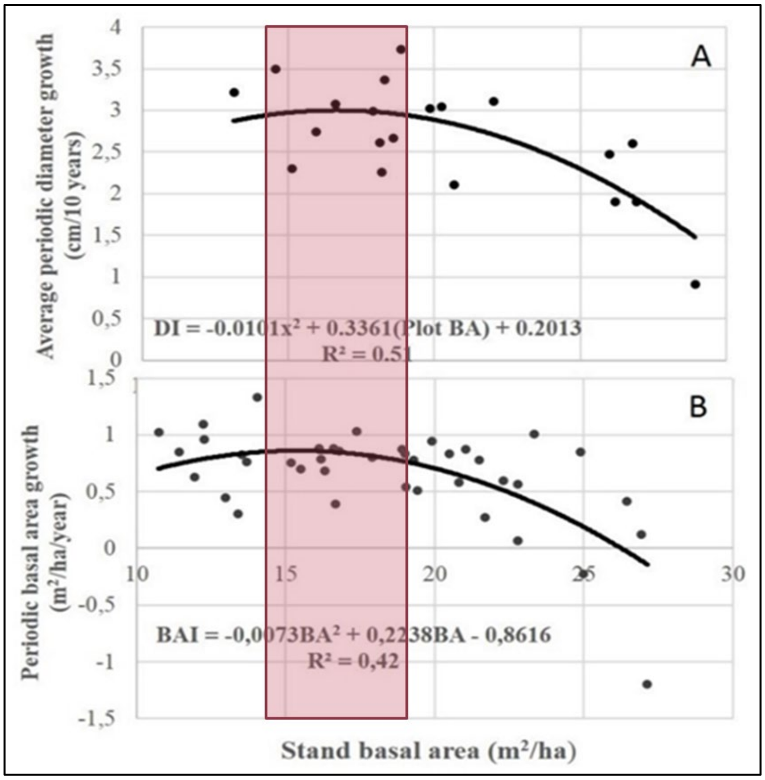


Figure 11. Optimal stand basal area affecting tree and stand growth

Concept no. 4. Tree vigour impacts stand and tree growth rates in interaction with tree size. The annual diameter increment is different for each species (Castle et al. 2018). There is a tendency for diameter increment to peak and then to decrease as the tree gets larger. In addition, trees with low risk of losing vigour have a higher diameter increment than trees with higher risk of losing vigour (Figure 12).

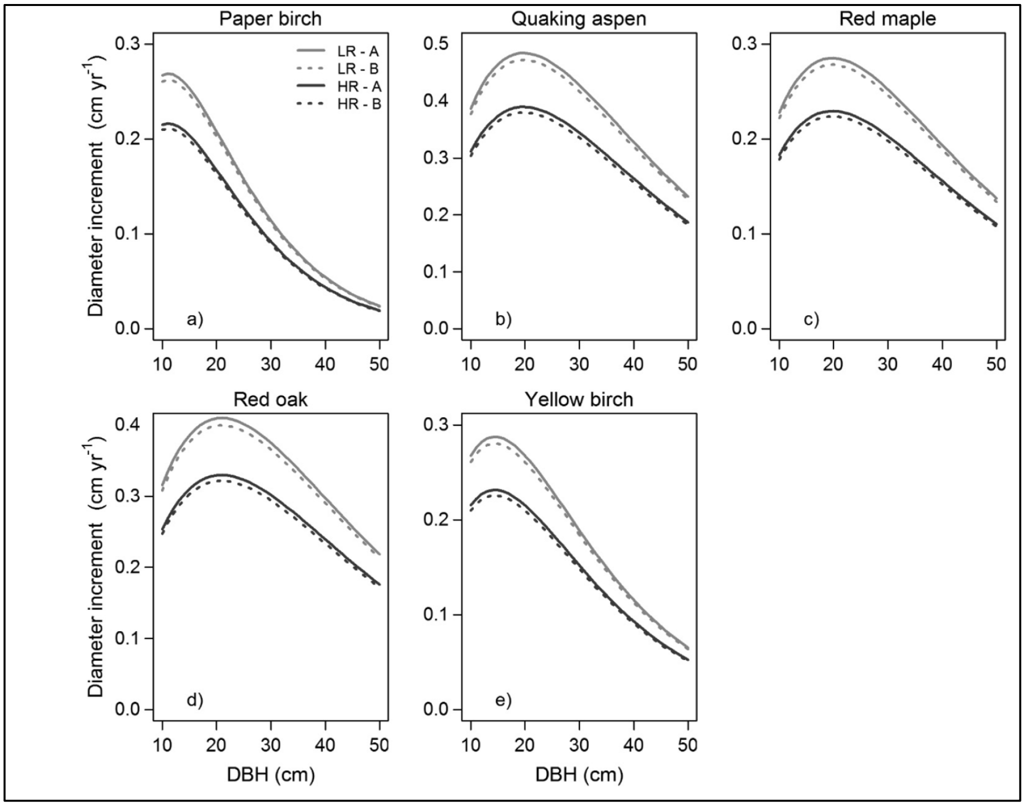


Figure 12. Tree vigour and size impacts growth rates (Source: Castle et al, 2018)

Concept no.5. Residual basal area impacts regeneration dynamics. Let's look at the relationship between the percent removal and the number of saplings by species after 20 years following partial cuts in northwest New Brunswick (Figure 13). A high harvest intensity will discourage American Beech, so the less basal area removed will promote Beech. Yellow Birch is the reverse. The more you open the stand the more you will regenerate that species. Sugar Maple has a very particular trend where it like the sweet spot in the middle. And then for Red Maple, there does not seem to be a significant trend. Understanding these trends is very important when deciding what silviculture regime to implement. For a tolerant hardwood forest with some softwood, recruitment of the new cohort if done by practicing uneven aged management with a selection cut for example (low harvest intensity) will lead to a high proportion of beech in the regeneration layer if beech is already present in the stand to some degree. On the other side, if the interest is to get a lot of yellow Birch, keep some Sugar Maple, and discriminate against Beech, the approach would be to an even-aged silviculture (high harvest intensity). But in the middle lies a range of moderate basal area removal and it is the two-aged extensive of irregular silviculture. It is where there are a lot of options in terms of insuring regenerations of desired species.

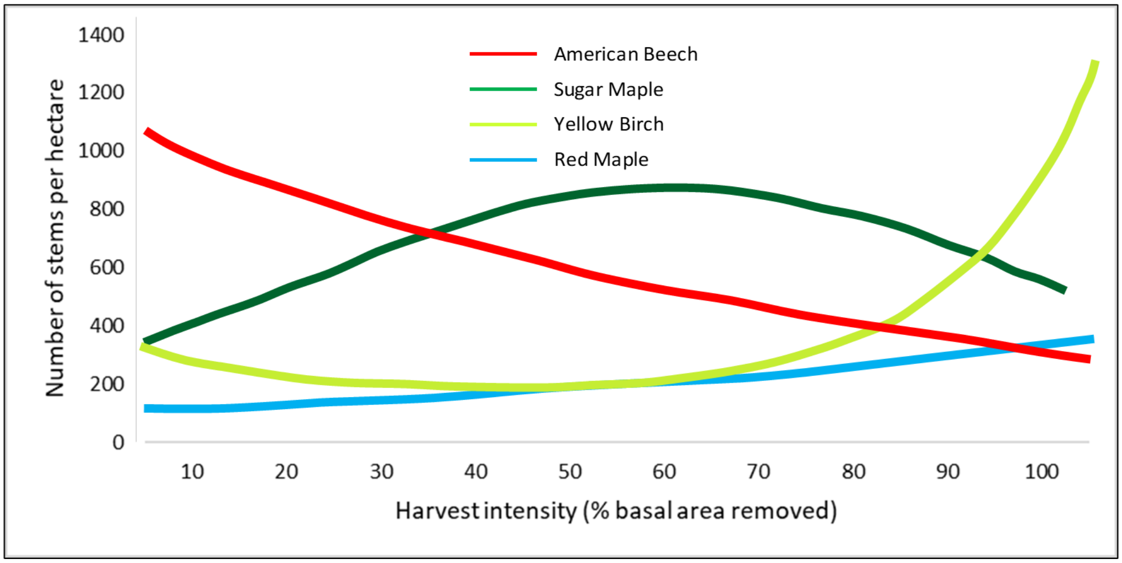


Figure 13. Regeneration success for different species in response to basal area removal

Concept no. 6. Crowns of crop trees must be released. The intensity of harvesting will provide additional resource to increase growth rate of residual trees and this impact will be different depending on the size of the residual tree (Eyre and Zilgitt, 1953) (Figure 14). A moderate canopy opening will result in better annual diameter growth than a patchy removal or no removal. And the effect is higher for smaller trees with diameters of 10-22 cm, compared to trees with moderate and larger diameters.

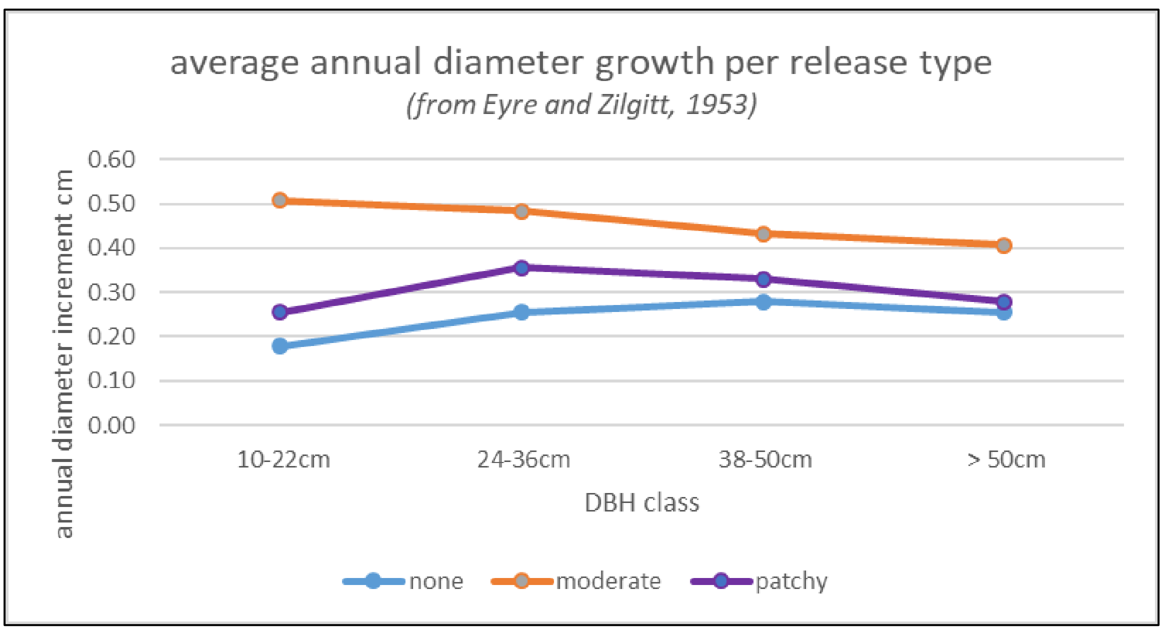


Figure 14. Average annual diameter growth per release type (Source: Eyre and Zilgitt, 1953)

But simply reaching the target average basal area for a stand is not adequate as a certain uniformity in the distribution of crop trees is needed. The crowns of crop trees need to be released by removing direct competition. This gets complicated when using mechanical harvesting systems where extraction trails are a necessity. Those trails need to be factored in and the ratio of trails to green strips must be considered. Trees in the green strips should be evenly spaced and their crowns released from the edge of the trail to the extend of the boom reach. It is important to release crowns of crop trees with a moderate to high intensity release to allow a good diameter increment (Figure 15).

Figure 15. Trail in harvesting operations

Concept no. 7. Harvest season, harvest season and trail network greatly impact regeneration establishment and creation of seed beds. In harvest-based silviculture treatment, where one of the goals is to establish a new cohort of trees, timing of the treatment is critical. Late winter operations, under heavy snow cover is not likely to benefit from soil mixing from the tracks of the machines. Apart from that, plan your trail network accordingly to increase the number of seed germination beds (Figure 16).

Figure 16. Germination bed characteristics in a harvesting operation trail

It is generally accepted that, at least for hardwood species, by the time a tree has reached 20 cm there is not much we can do to improve its quality, its growth and health status. Where we can have the most impact is at the regeneration level and at the sapling stage. A pyramid of silviculture priorities actions and tasks can illustrate and rank the priorities (Figure 17). At the very bottom of the pyramid, at the foundation, we find three important actions: regenerating desired species, protecting crop trees, and reducing the risk of losing value of crop trees. This is where resources should be put. Promoting the right core of trees is the most single important thing to do.

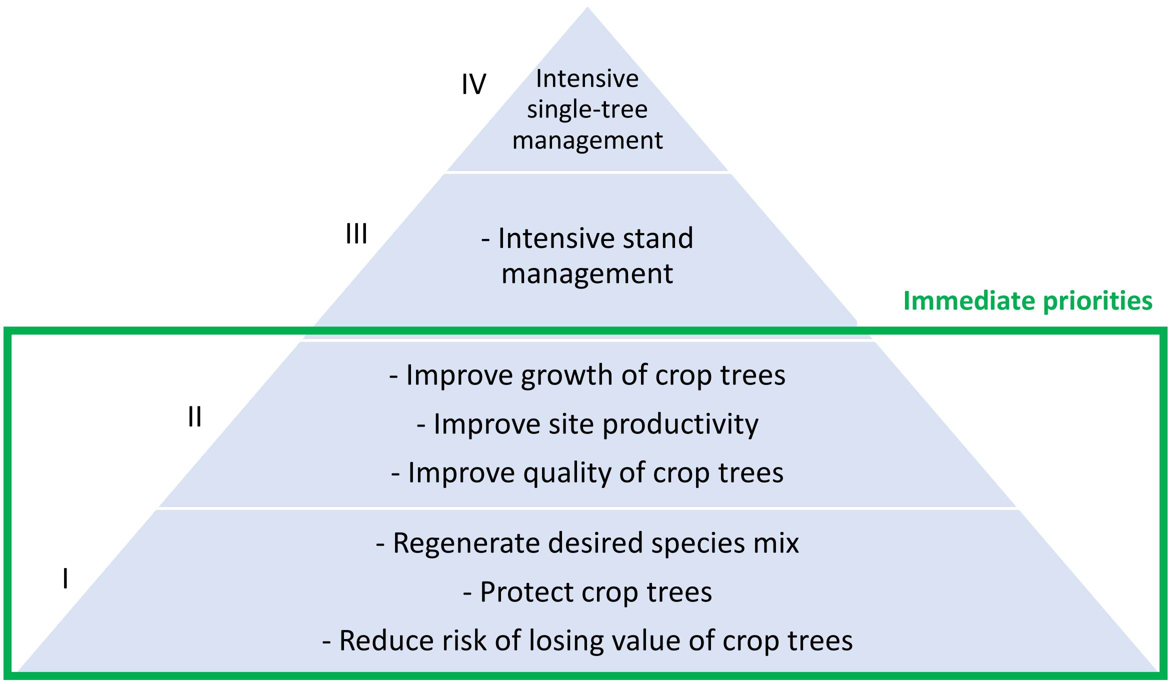


Figure 17. Hierarchy of silviculture priorities for hardwood stands.

5. ADAPTIVE MANAGEMENT

The other piece about adaptive silviculture is the adaptive management part. And it is not a new concept, it's been around for probably 4 to 5 decades and it fits really well where you have a high uncertainty about the outcomes, but you also have a high degree of controllability (Williams et al, 2012). (Figure 18). Creating a framework of adaptive management represents a good approach meeting the two criteria (Figure 19).

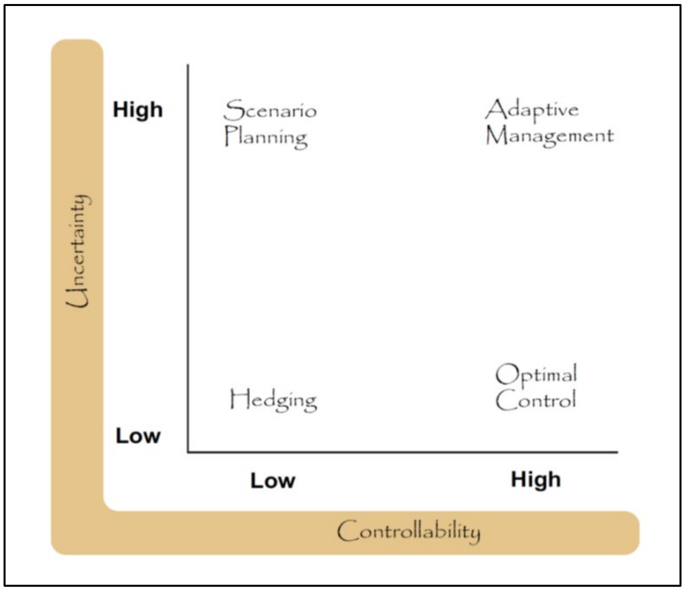


Figure 18. Different approach with different degree of uncertainty and controllability (Source: Williams et al, 2012).

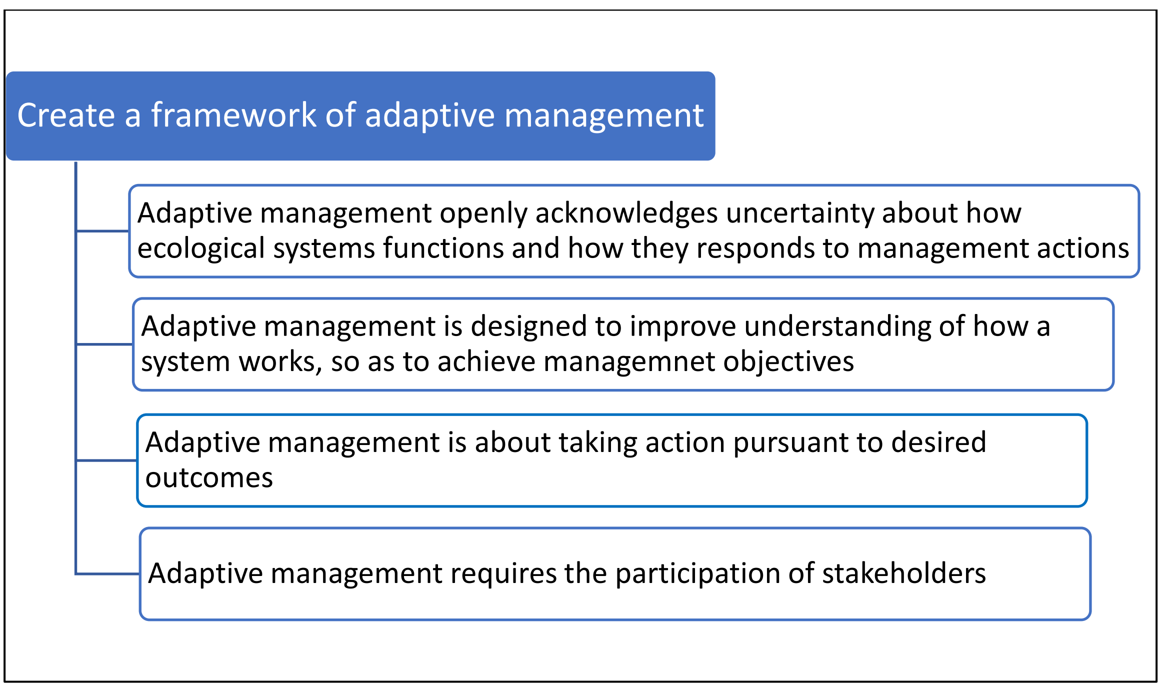


Figure 19. Adaptive management framework

The steps are not complicated. Since 2014, the province of New Brunswick has started in the direction of implementing a framework on adaptive silviculture. The adaptive silviculture has several steps (Figure 20). First, understand what you have today and asses the problem. Then decide how many solutions you want to explore and implement one or two or several solutions. Monitor the performance of the outcomes. Evaluate the effectiveness. And finally, adjust to make improvements by readjusting and do the cycle again. That is the principle of adaptive management.

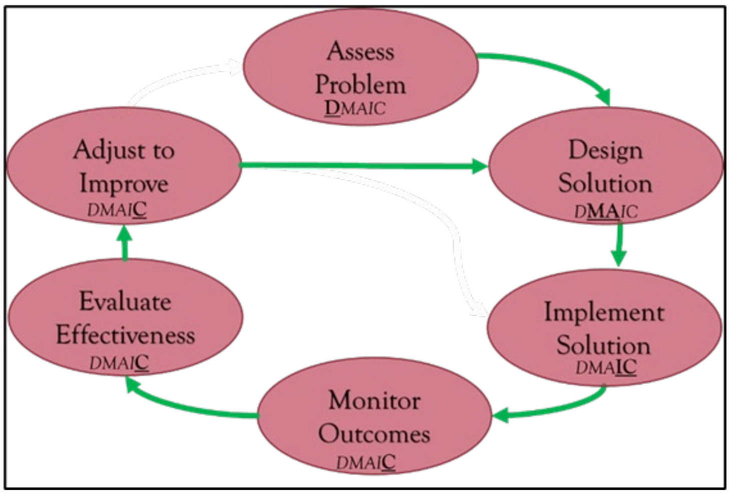


Figure 20. Framework of adaptive silviculture

It has been documented in recent history in the US and in Canada, that this approach works well in adapting our forests in light of a changing climate. The Americans have done a ton of good work on that under the leadership of the state forest service. It really details how to implement adaptive silviculture to forests under a changing climate (Janowiak et al. 2014) (Figure 21).

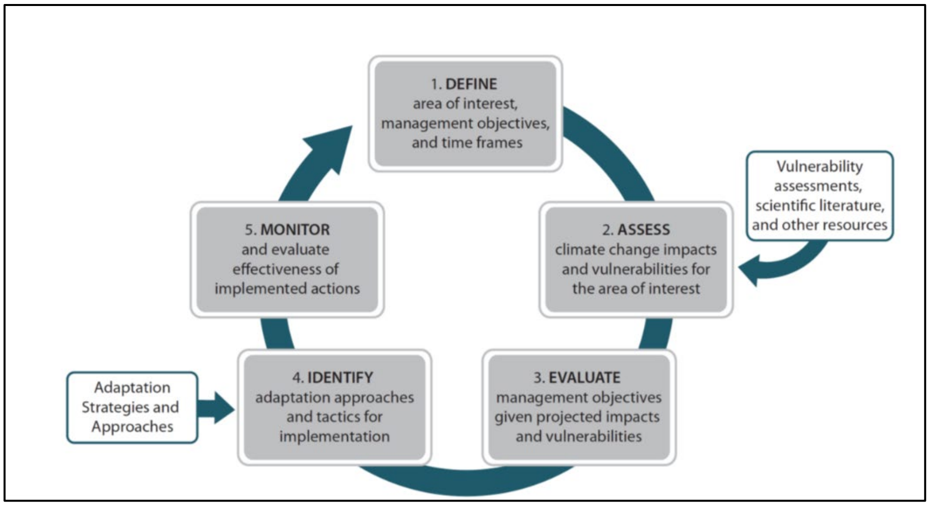


Figure 21. Implementation of adaptive methods (Source: Janowiak et al. 2014).

One of the goals of adaptive silviculture at the tactical scale, is to work at the fine level such as the ecosite level. The edatopic grid of ecosites is useful to situate ecosite according to topoclimate, nutrient regime and moisture regime on the two axes (Zelazny, 2007) (Figure 22). We ca use that and predict what will be happening at a regional scale. A changing climate is at a regional scale. One stressor event, like an increase in temperature, can be good in some places but bad in other places. Same principle with prediction in different precipitation levels.

If for example, we take ecosite 8 which is very rich and dry with an increase in precipitation levels that is a good thing for Sugar Maple since ecosite 7 is appropriate for that species. But if we take ecosite 7 which is already kind of wet, it is very good today for Sugar Maple and Yellow Birch but if it gets wetter because there is more water available in the soil, then it gets bad for those species. So, this framework is very useful to assess the different scenarios.

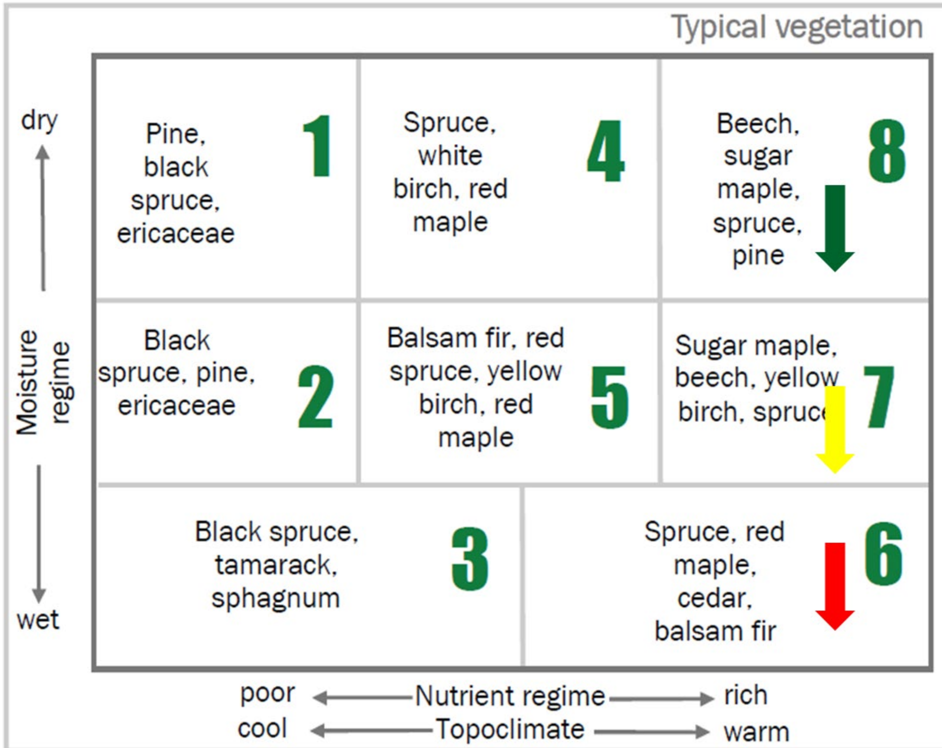


Figure 22. Edatopic grid of ecosites (Source: modifies from Zelazny, 2007)(Green arrow means a favorable change for Sugar Maple, yellow means moderately favorable and red means not a favorable change)

6. PATHWAYS ANS APPROACHES

Once you understand those impacts, then you can decide which pathways you want to consider. In the context of forest management, adaptation approaches occupy a continuum of management goals related to their levels of desired change. They provide intermediate “stepping stones” that enable managers to translate broad concepts into targeted and prescriptive tactics for implementing adaptation (IPCC, 2001). Which approach best prepares forest ecosystems for climate change? When it comes to adapting our forest management to reduce the negative impacts of climate change, we can consider three main approaches or pathways – apart from the “do nothing” scenario (IPCC, 2001). The approaches are: increasing forest resistance to negative impacts, increasing resilience with respect to current and future changes and promoting transition of our forests to a new state (Figure 23). It becomes clearer if you have a regional perspective based on your knowledge of ecosites and some predictions.

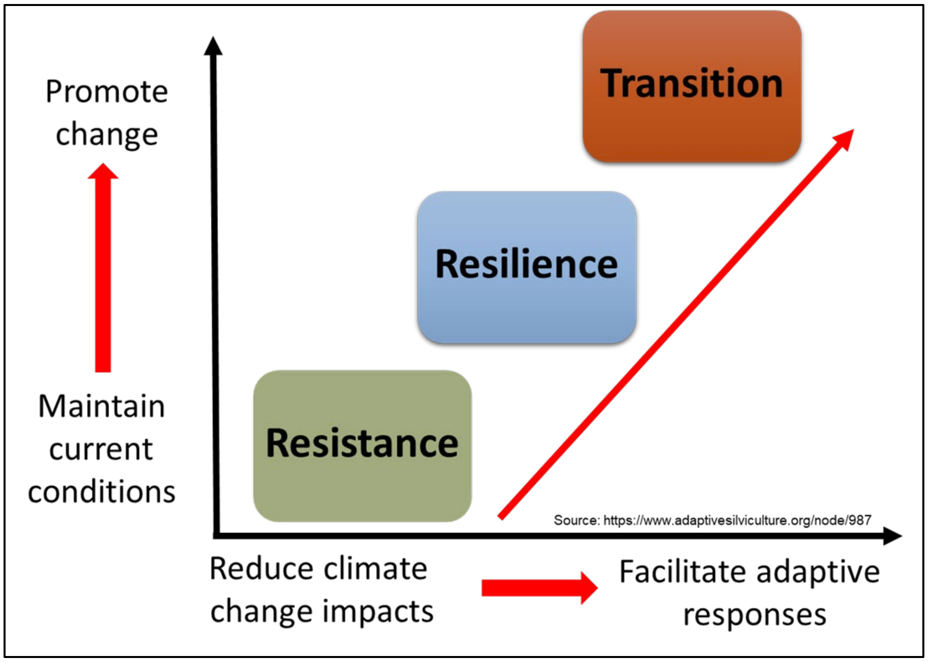


Figure 23. Three approaches of adaptive silviculture (Source: http://forestry.sfasu.edu)

The resistance approach is a group of actions that improve the defense of the forest against anticipated changes or against disturbance in order to maintain relatively unchanged conditions (Adaptive silviculture for climate change, no date). The resistance option typically involves investing resources into maintaining what is currently on the landscape. Over time, the effort and resources needed to maintain forests in their initial conditions will increase – meaning this approach could become increasingly costly as climate changes into the future. The resistance option is best utilized as a short-term strategy or to maintain resources of high cultural, economic, or ecological value.

A disturbance is defined as any relatively discrete event in time that disrupts the ecosystem, community, or population structure and changes resources, substrate availability, or the physical environment (Figure 24). For example, Mount St. Helen's volcano eruption is something very severe but not frequent. At the other end, we have single tree blowdown, which is frequent but not as severe.

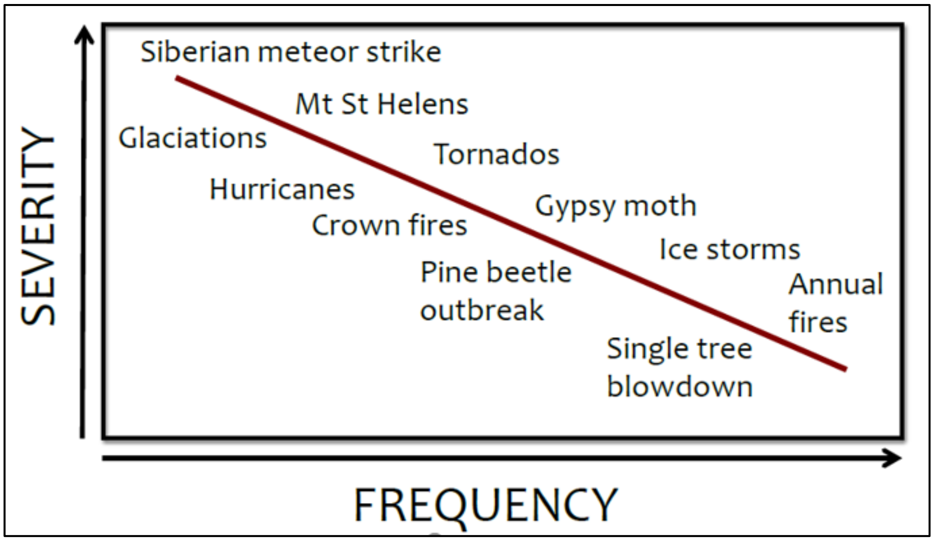


Figure 24. Severity and frequency of disturbances (Source: Source: SAF Dictionary: www.dictionaryofforestry.org)

When looking at productivity, like total biomass production over time (Figure 25), the start of the blue line refers to the current conditions of a specific stand. If no treatment is done to the stand, when the stand faces a disturbance, the productivity will decrease relatively fast because the stand was not prepared to face such a disturbance (blue line dropping in productivity). But with the resistance approach (green line) a treatment is done before the disturbance occurs, for example a drought period. At that time, the ecosystem still functions, and conditions will remain relatively stable. But over time, as the disturbance becomes more severe, the resistance approach will reach its limit, leading to major changes in forests conditions. The objective of the resistance approach is to increase tree and stand resistance to stressors like: drought, insects and diseases and strong winds that climate change may amplify the frequency and severity over time. Silviculture practices to improve forest resistance means to control elements that can be managed using silviculture practices to improve forest resistance. That means stand structure and stand composition. The silviculture practices include precommercial thinning, commercial thinning and partial cutting.

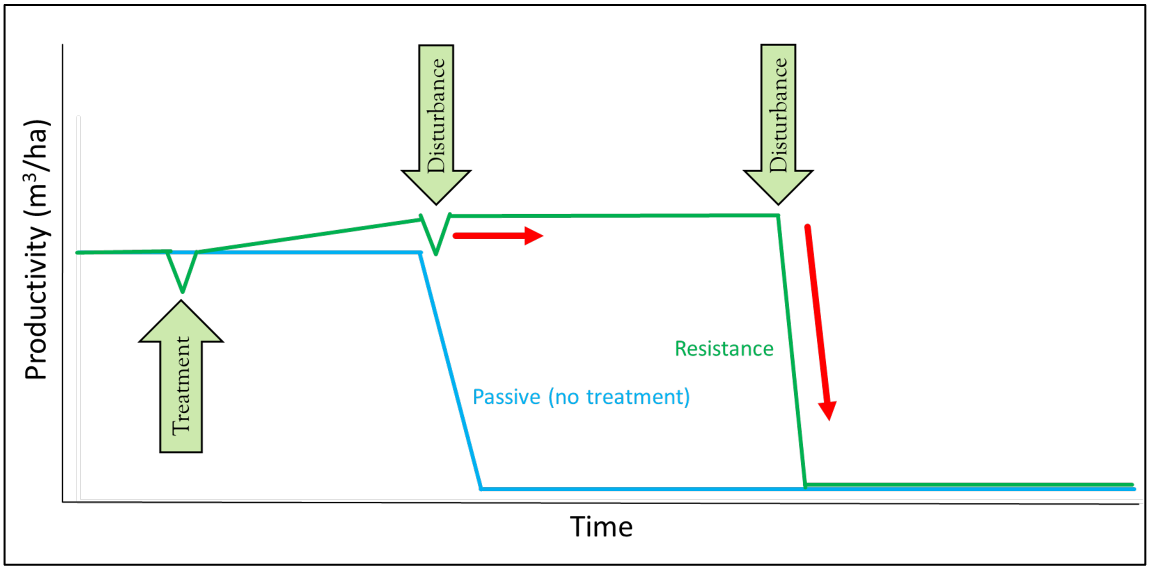


Figure 25. The resistance approach (Adapted from http://forestry.sfasu.edu)

For example, a stand with healthy and vigorous trees with good growth rates will withstand cumulative stress better than those already competing for resources. If we want to improve resistance to drought, the simplest method is to thin at different times in the lifecycle of the stand, reducing competition for key resources. Crowns will develop more fully, enabling the tree to transform CO_2 more effectively into carbon through photosynthesis (Figure 26). Having fewer trees on one micro-site also reduces competition for water. Thinned stands will also reach economic maturity sooner, allowing for subsequent adaptation silviculture earlier in the rotation, to further reduce risk. This practice is well suited to most tree species.

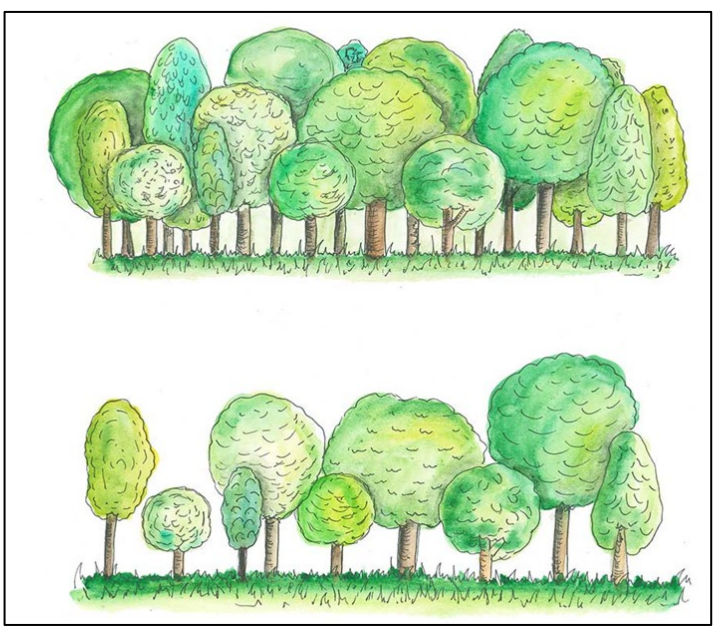


Figure 26. Development of crown after silviculture treatment (Source: https://www.fwi.co.uk)

Another example is partial cut. Partial or selective cutting in hardwoods stands is a bit more complex then thinning in softwood stands. The main reason: it is not always easy to identify the signs and/or symptoms that characterize weak trees. Just looking at fungi is a world in itself. A Sugar Maple tree can be affected by two different fungi with two totally different outcomes. The *Pleurotus oastreatus* fungi (Figure 27) is annual and inoffensive. It is not even taken into consideration when assessing detailed tree health. On the other hand, the *Kretzchmaria deustra* fungi (Figure 28) causes decay in Sugar Maple tree very quickly and it can result in sudden stem breakage I otherwise apparently healthy trees.

Figure 27. *Pleurotus oastreatus* on Sugar Maple

(Source: Boulet, B. & Landry, G. 2015)

Figure 28. *Kretzchmaria deustra* on Sugar Maple.

(Source: Boulet, B. & Landry, G. 2015)

The objective of improving health and vigour of our forests combined with a certain degree of diversity in the forest composition is a sound approach of adaptive management to make our forests more resistant.

The second approach is the resilience approach (Figure 29). The resilience approach is the group of actions that accommodate some degree of change but encourage a return to prior condition or desired reference condition following a disturbance. The resilience approach presents different phases. After a silvicultural treatment there will be a small drop in productivity, but it will be recovered with a rapid return to reference conditions and even a following increase in productivity. After a disturbance event, for example a drought event, an important drop in productivity will occur followed by a return to initial conditions. However, the amplitude of the effect from the second disturbance will be less important than the first one. Then over time, if disturbances continue to increase, the productivity will reach the lowest level.

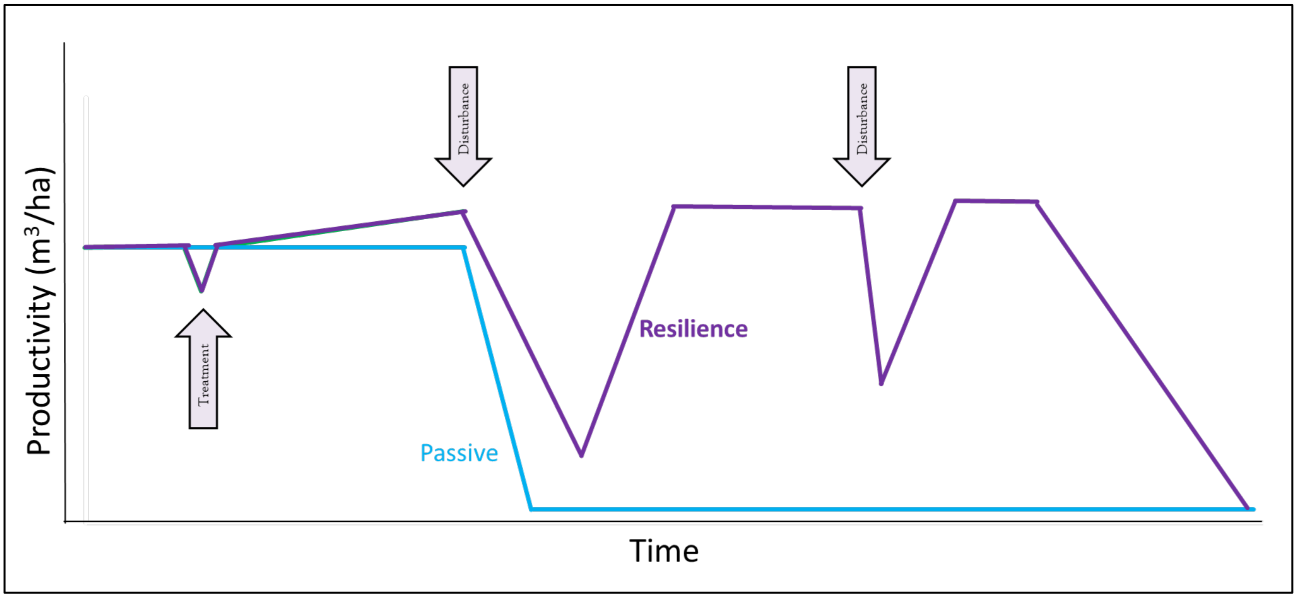


Figure 29. The resilience approach (Source: http://forestry.sfasu.edu)

This adaptation strategy will promote diverse age classes. Species are vulnerable to stressors at different stages in their life cycle (Adaptive silviculture for climate change, no date). Even-aged stands are often more vulnerable to insect pests and disease, many of which are likely to increase in range and severity as a result of climate change. In uneven-aged stands, a smaller proportion of the population may be exposed to a particular threat at any one time, which can increase the resilience of a stand to a wider range of disturbances. For example, for an uneven-aged stand, the result of an eastern spruce budworm outbreak will be less important compared to an even-aged stand. In fact, the diverse mix of forest types, age classes and stand structures reduces the availability of host species for pests and pathogens.

The resilience strategy will also restore ecosystem productivity. An important change in temperature or a lightening event can set off a fire. In this case, using a salvage operation can enhance regeneration. Another way can be by applying site scarification, planting or other techniques to support adequate regeneration.

And finally, the strategy can be used to maintain diversity of desired species. By planting desired native species such as Red Spruce, White Spruce and Black Spruce, within an area that is otherwise expected to regenerate with undesired species.

The third approach is the transition approach. The transition approach represents the process of changing from one state to another. A stand may be presently a mixed stand for example, but the silvicultural treatment applied may lead to a different stand structure to better cope with the effects caused by climate change. With the resilience approach (Figure 30), after the appropriate treatment, there will be a big impact on productivity. But over time the productivity will then keep increasing even if disturbance events occur due to climate change.

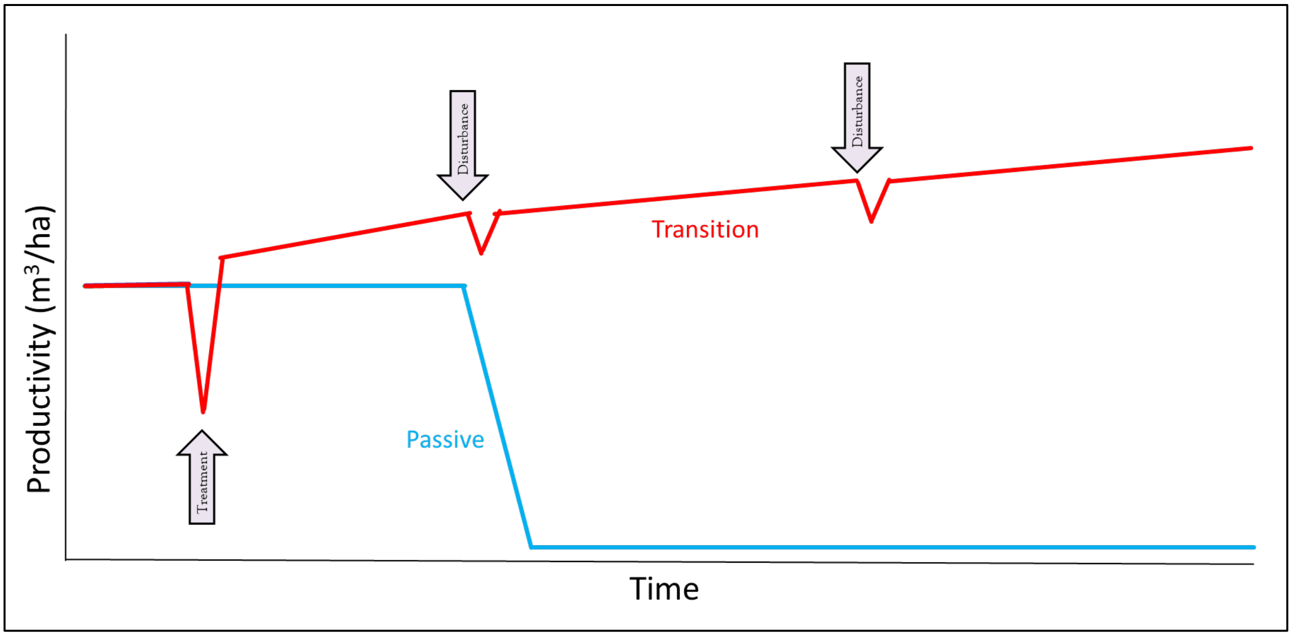


Figure 30. The transition approach (Source: Adapted from http://forestry.sfasu.edu)

The objective of the transition approach is to intentionally accommodate change and enable stands to adaptively respond to both new and changing conditions. This approach is really trying novel techniques to identify the best ones to meet management objectives. For example, we may apply a silvicultural treatment in a softwood stand and with climate change the trees will eventually die and hardwoods will regenerate and establish (Adaptive silviculture for climate change, no date). So, with the transition approach, productivity in increased as we see bigger trees in a shorter time lap (Figure 31).

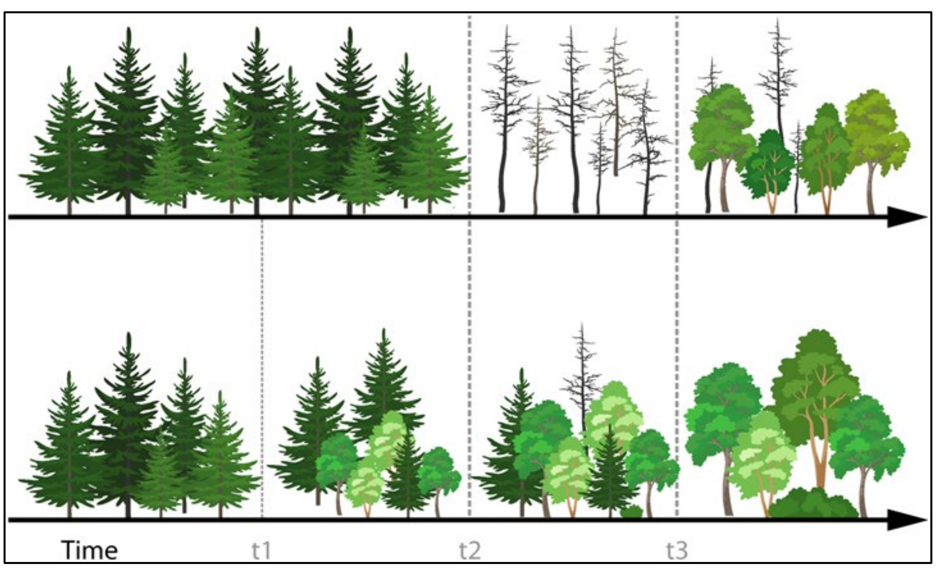


Figure 31. Increased productivity with silviculture treatment (Source: : Jandl *et al.* 2019)

The benefits of the transition approach are to increase the adaptive capacity of the stand. The disadvantage means more efforts need to be put upfront, but then a decrease of efforts over time. So, a big change will result in the stand at first but aver time the stand will adjust itself. It is also the most radical and it is potentially risky because of uncertainty of the prediction of the climate change effects (Adaptive silviculture for climate change, no date).

So where do we apply the transition approach in forest stands? It is not an approach to apply in every stand conditions. But in some areas, it is possibly the best one to chose. It should be applied in cases where we need artificial regeneration, or we need to start over. It can also e chosen in areas where vulnerability to climate change is high. So, for example, it is projected that by 2100 there will be a low probability of occurrence of White Birch in New Brunswick (Figure 32). As compared to Red Maple where the probability of occurrence will remain relatively the same as today (Figure 33). A mixed wood stand with a large proportion of White Birch would be an excellent case to apply the transition approach. But a stand with a large proportion of Red Maple would not qualify as the recommended approach here would be to keep the same composition (Adaptive silviculture for climate change, no date).

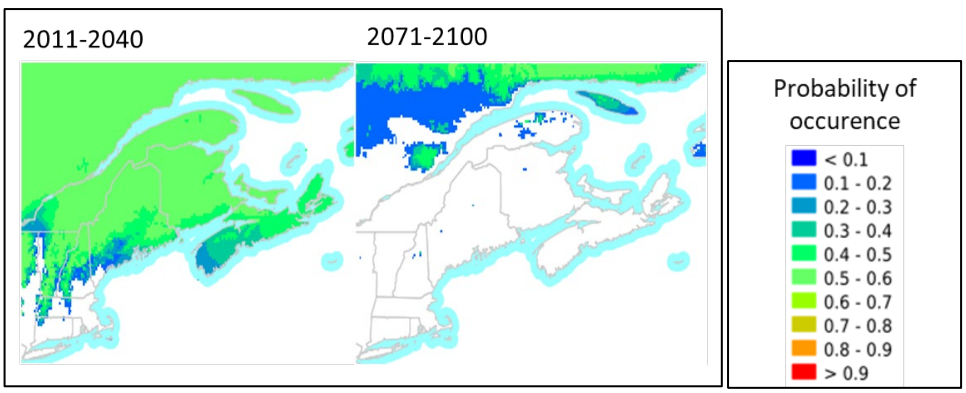


Figure 32. Probability of occurrence of White Birch from 2011 to 2100 (Source: www.planthardiness.gc.ca)

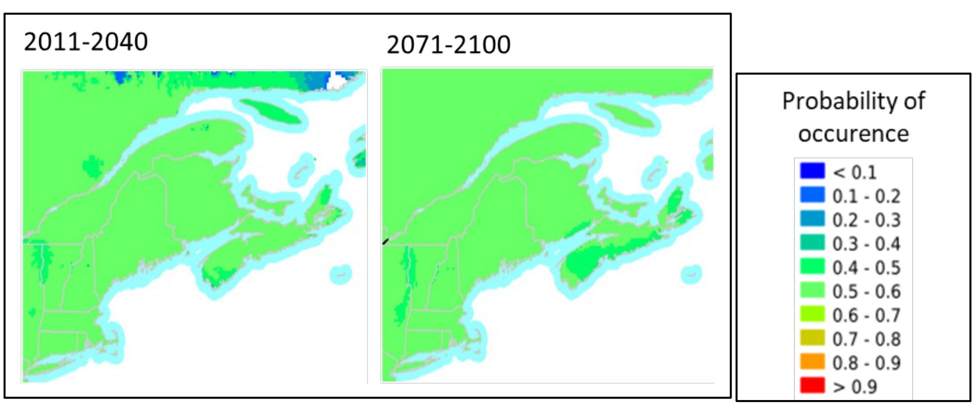


Figure 33. Probability of occurrence of Red Maple from 2011 to 2100 (Source: www.planthardiness.gc.ca)

The transition approach is based on the concept of assisted migration with the introduction of new species or new individuals of the same species that are better adapted to the new conditions. For example, if we need to plant White Spruce, we would choose seedlings that come from the seeds from southern Maine because they are probably more adapted to a warmer climate (Figure 34). This approach also offers the possibility to change species composition.

Figure 34. Distribution of White Spruce (Adapted from: www.fs.fed.us)

Let's not forget that there is some uncertainty around climate change and its potential impacts on the forests. More research is needed but the transition approach offers a tool to prepare stands to be better adapted to remain productive even with the occurrence of climatic disturbances.

7. IMPLEMENTING ADAPTIVE MANAGEMENT

So really, the hart of it is to practice the best silviculture possible. Implementing adaptive management is a very powerful tool. Especially when combined with good quality silviculture embedded in systems and regimes. To implement adaptive silviculture, it is important to follow some recommendations (Figure 35).

1. PRACTICE GREAT SILVICULTURE AT THE TACTICAL SCALE
    a. Short rotations are OK sometimes
    b. Increase site productivity
    c. Reduce uncertainty and risk
    d. Choose silviculture regimes with multiple entries when in doubt
    e. Use intermediate treatment in your favour
2. IMPLEMENT ADAPTIVE MANAGEMENT
    a. Create an infrastructure to facilitate learning
3. PLAN-DO-CHECK-ACT
4. BEGIN NOW

Figure 35. Recommendations when implementing adaptive silviculture

8. AN EXAMPLE OF HOW TO IMPLEMENT ADAPTIVE SILVICULTURE

To illustrate how to implement adaptive silviculture, a concrete example is presented as a 9,4 hectares woodlot in northern New Brunswick (Figure 36). Stand stratification is very important and so is the scale at which silviculture will be applied. For the woodlot in question, we have ecosite 7 and ecosite 8 which are rich in nutrients and calcium (Figure 37). Ecosite 8, which covers most of the area is a dry ecosite. Ecosite 7 is slightly moistier. Both ecosites are conductive to growing Sugar Maple and tolerant hardwoods although there is a mixture of many species now.

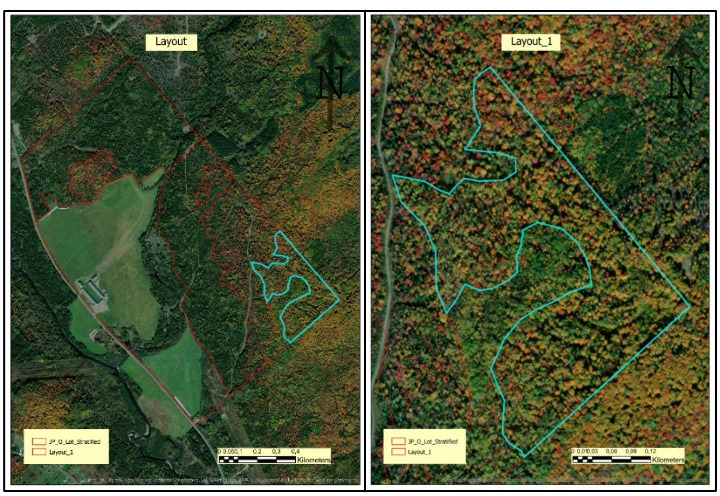


Figure 36. Private woodlot in Northwestern New Brunswick

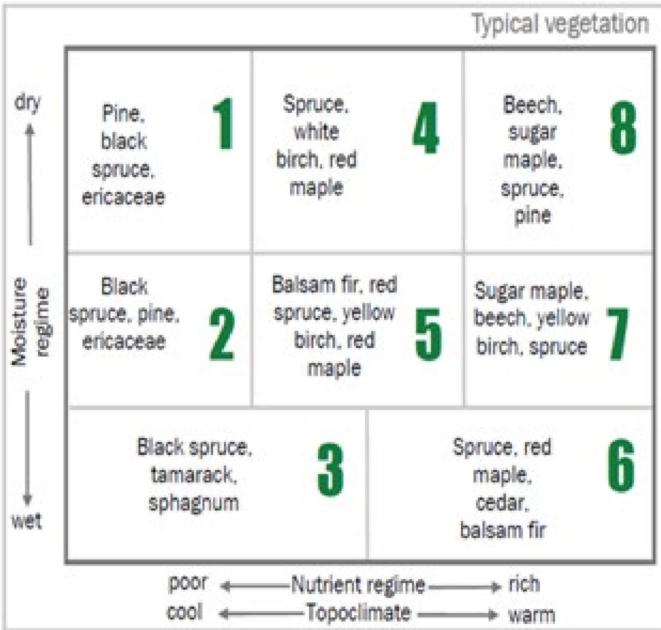
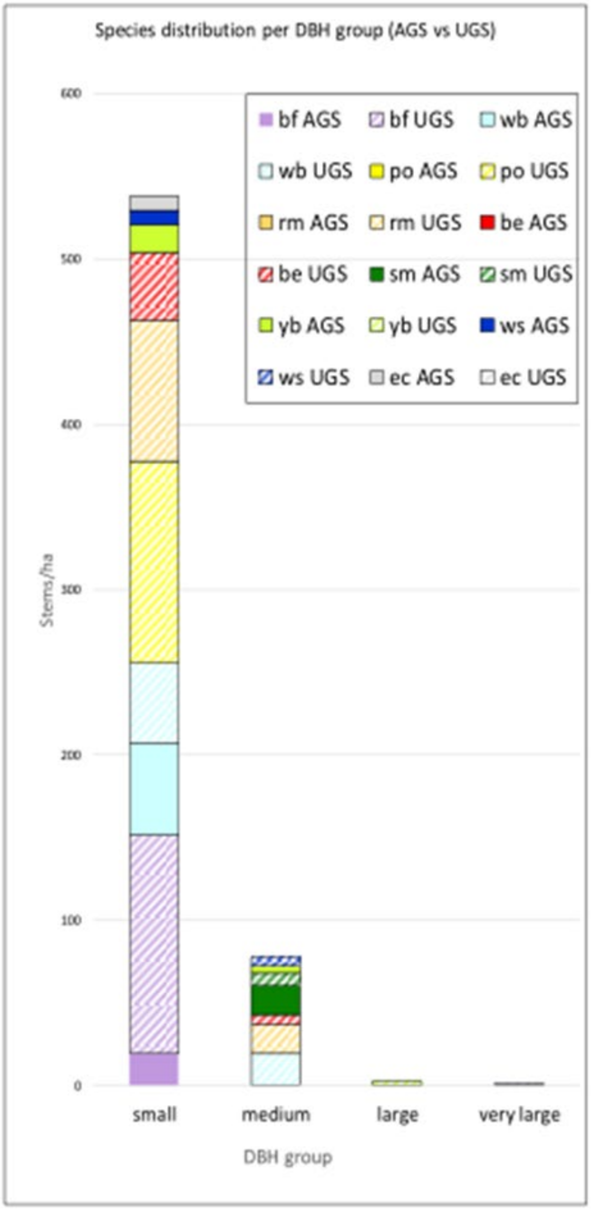


Figure 37. Edatopic grid of ecosites (Source: Zelazny, 2007).

A standard forest inventory has been done and the species distribution and the quality assessment are presented (Figure 38).

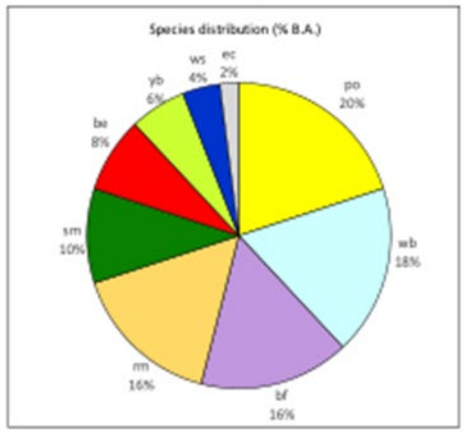


Area (ha)	9.44
Stems/ha	620
Basal area (m2/ha)	16.7
QMD	23.1

	Volume per hectare (m3/ha)		
Species group	Merch. Vol.	Sawlog Vol.	Pulp Vol.
HW	80.20	21.96	58.24
SW	21.60	5.90	15.70

	Total volume (m3)		
Species group	Merch. Vol.	Sawlog Vol.	Pulp Vol.
HW	757.09	207.35	549.74
SW	203.89	55.71	148.18

Species group	% AGS	%UGS
HW	21%	79%
SW	36%	64%



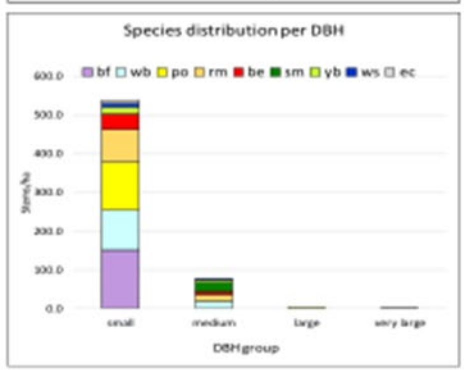


Figure 38. Inventory data of the woodlot

Additionally to standard data, a lot of LiDAR data is available without having to set foot in the forest. All kinds of derivatives of LiDAR point cloud data can provide slope, aspect, contours, Biomass Growth Index that addresses site fertility, and depth to water table (Figure 39). These variables are great indicators of site productivity and they classify the study area as having a very good potential level of productivity.

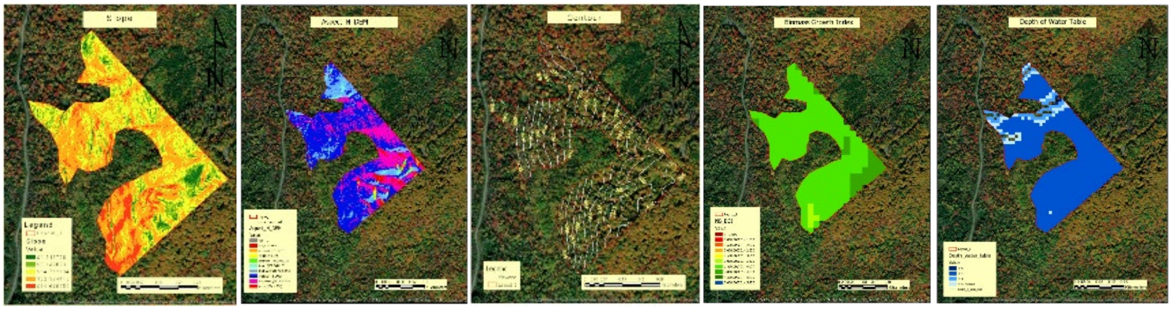


Figure 39. LiDAR derived data

And also, there is an additional layer available, it is the forecast of the probability of species to be present in the future in a given area but based on the historical presence. So, affinity maps were produced for this woodlot to show probability occurrence of six species: Balsam Fir, White Spruce, Yellow Birch, Sugar Maple, Red Maple, and American Beech (Figure 40). This reflect the growth abundance of desired species in the future and is a useful information at a very small scale.

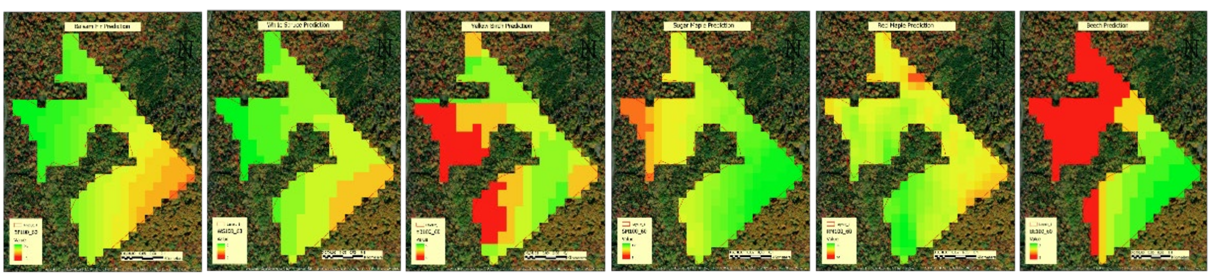


Figure 40. Probability of species occurrence

The next step is to assess climate change impacts and vulnerability for the area of interest (Figure 41). So now, do we adjust for species composition? Going back to the inventory data (Figure 38), Trembling Aspen represents 20% of the tree inventory and it will most likely decrease according to predicted trajectory. White Birch and Balsam Fir are also going to decrease in proportions in the future. They are represented with green arrows because this is not a bad event if they are going to drop. And then there is a little bit of Red Maple. The trend will be upward so the proportion will increase. However, Sugar Maple is represented by only 10% and unfortunately it is forecasted to go down in proportion with climate change. Yellow birch will remain stable even with climate change. American Beech will increase, and this is not good news because of the low commercial importance and the risk associated to Beech bark disease. These forecasted trends will happen if no silviculture treatments are applied. So now, with this information and all the other layers of information we are now better prepared to tweak our silviculture that will be applied to this area.

Species	%	Predicted Trajectory
Trembling Aspen	20%	↓
White Birch	18%	↓
Balsam Fir	16%	↓
Red Maple	16%	↑
Sugar Maple	10%	↓
American Beech	8%	↑
Yellow Birch	6%	✓

Figure 41. Present composition of species and projection

The changes in species composition are related to forecasted variation in climate variables for the next 80 years (Northwest Regional Service Commission) (Figure 42). Among those, the number of freeze-thaw days is forecasted to go down for the Madawaska ecodistrict which is good. Cycles of freeze-thaw days in the winter can cause great damage especially for sugar maple. The average winter temperature is forecasted to go up. The annual precipitation is going up in the future. And so is the average annual temperature. Soil moisture content goes up and so is the growing degree days. All these predicted changes in key climate metrics can be linked to specific ecosites and affects the future proportions of species (Figure 37).

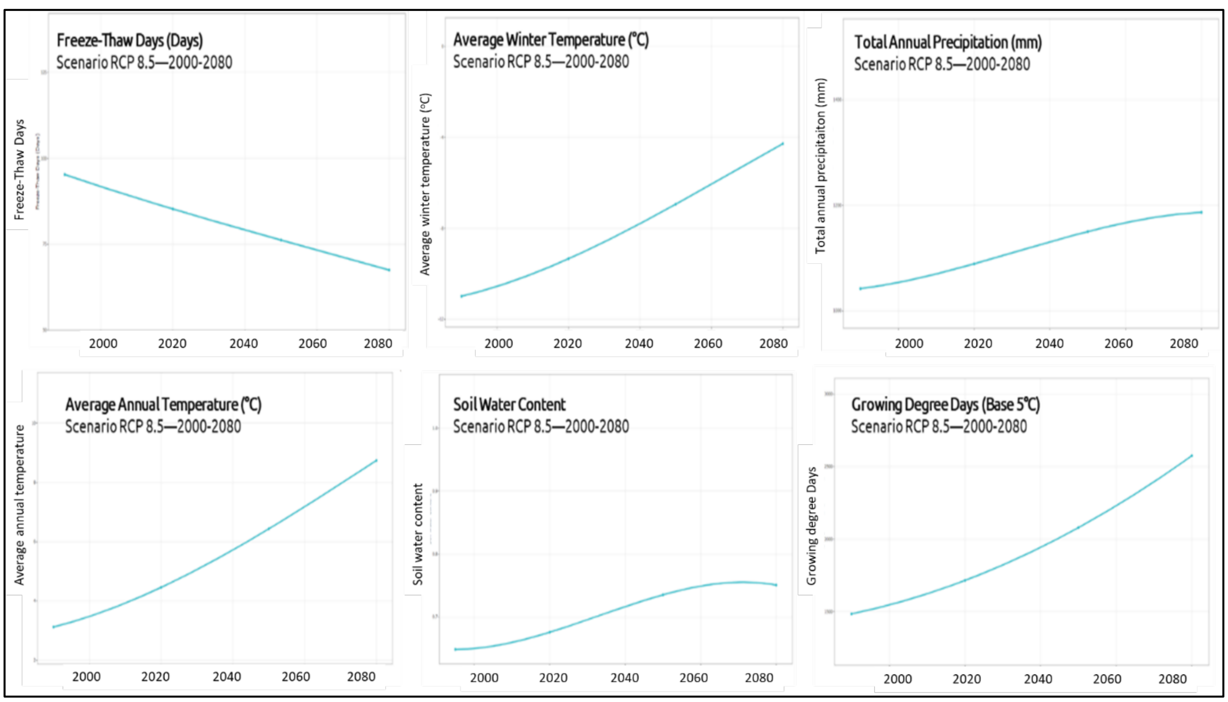


Figure 42. Predicted climate variables for the next 80 years (Source: Northwest Regional Service Commission www.csrno.ca)

Before we choose which silviculture systems to implement, we must keep in mid that the % of basal area removed will greatly impact the recruitment regeneration species (Figure 13). With a high basal area removed, American Beech and Sugar Maple will decrease in stems. Red Maple will increase slightly but Yellow Birch will show an important increase. In the case of the present woodlot, the best regime to recommend is a uniform shelterwood regime followed by a commercial thinning. That gives a timeline of treatments (Figure 43). The idea is to verify at check points and change course if needed. There is a ton of opportunities in this regime to switch things around if the results are not as desired. And in each step, actions can be taken to change composition, change the vigour of trees and others.

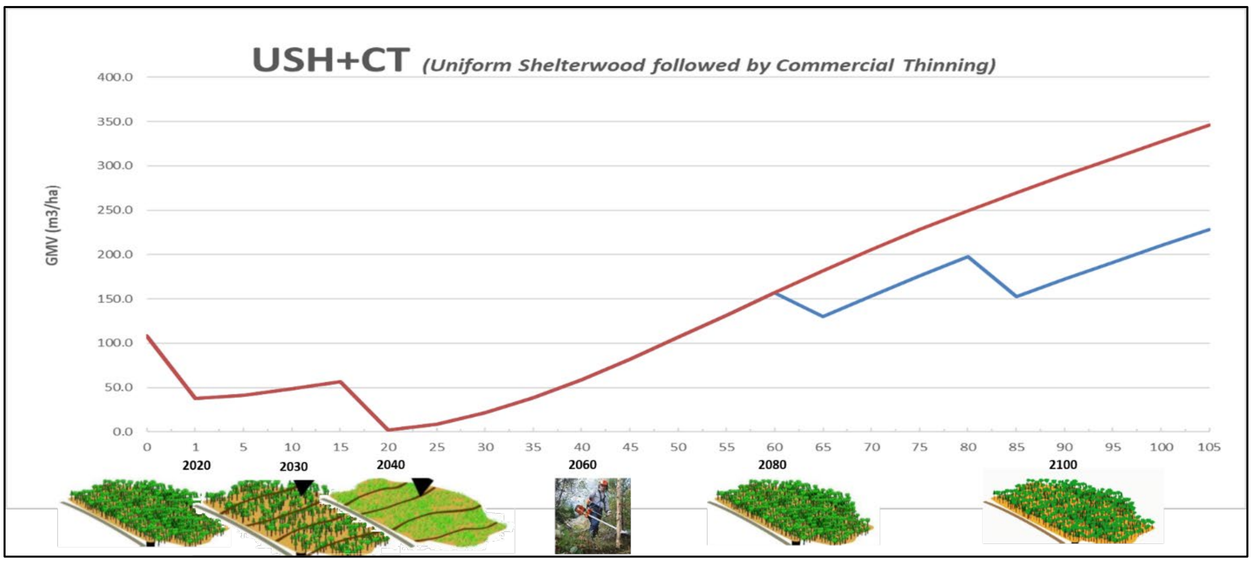


Figure 43. Timeline of treatments (Uniform Shelterwood followed by commercial thinning) (Adapted from Lessard et al. 2013)

9. GENERAL RECOMMENDATIONS

In general, it is important to consider also irregular forest silviculture. It could be a silver bullet. It is important to consider what to change, what cohort is being recruited and use that to keep the trees of good quality that are already there. And if implemented right, that regime alone can be as much as a silver bullet.

The overarching goal is to restore our degraded forests through harvest-based silviculture to recruit new cohorts of interest and maintain/release existing acceptable growing stock. The steps are as follows (Figure 44):

1. Depending on stand characteristics, open up the stand more than usual;
2. Recover trees with products at risk of losing value;
3. Release pole-size, small and medium acceptable growing stock;
4. Create germination beds;
5. Conduct intermediate treatments when saplings are well established;
6. Encourage the establishment of a second cohort;
7. Transition into continuous cover.

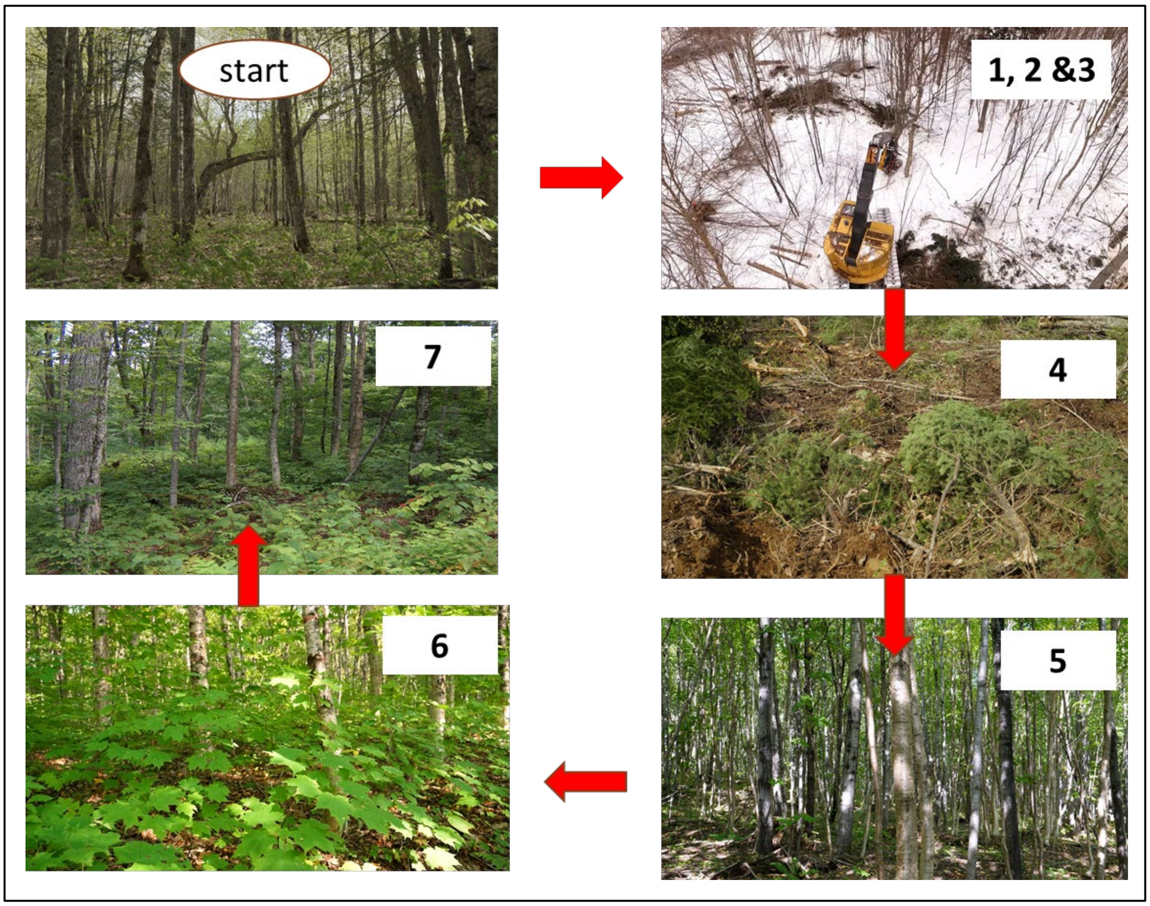


Figure 44. Steps for recruitment of a new cohort

The irregular silviculture has many variants (Lessard et al., 2013)(Figure 45). It is recommended that the continuous two-aged, which is really a continuous cover shelterwood be the variant of choice. This seems to be the one single regime that fits almost any forest type. In the past five years, in around 3000 hectares cruised in New Brunswick, 2/3 of the time, this type of silviculture regime and silviculture system was recommended.

So what is the irregular silviculture? It is a process of regeneration. It consists of successive partial cuts used to establish regeneration. It maintains a protective cover, spread over a period of time exceeding 1/5 of the rotation of the stand. The steps are: 1) seed establishment cut; 2) one or more secondary cuts and 3) final cutting but in different parts of the stand.

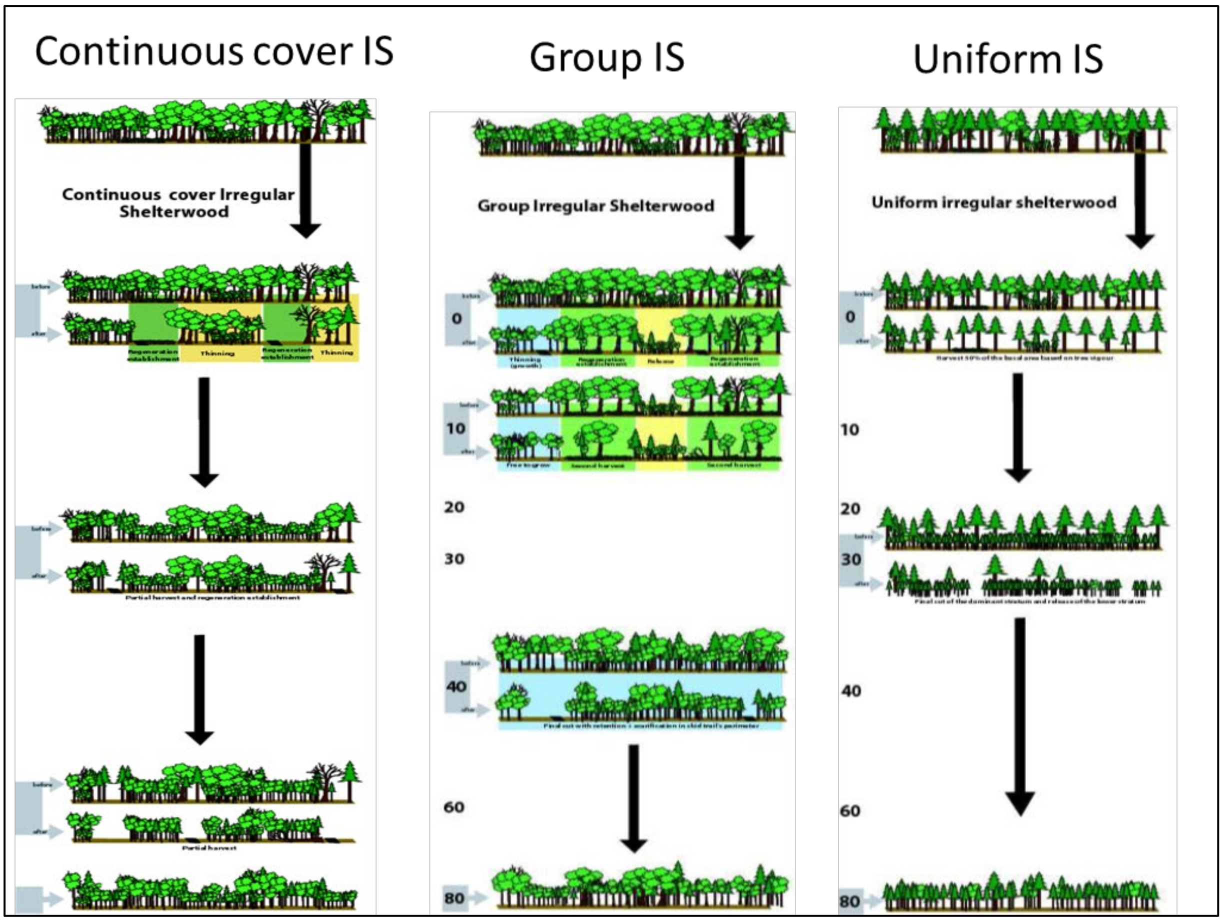


Figure 45. The irregular shelterwood (Adapted from Lessard et al. 2013)

10. CONCLUSION

Recommendations have been published over the years for adapting silviculture to climate change. Most recommendations are either general of tailored to a specific forest management context regarding climate objectives. Climatic variations and their effects on the distribution of forest species have been predicted for the next 80 years and it is clear that species will be affected in different ways.

Based on these assessments, natural resources managers can identify opportunities and challenges in reaching their management objectives. A reconsideration of original objectives can lead to adaptations of current silvicultural actions. The presentation of a case study showed hos to implement adaptive silviculture with considerations to predicted climatic variables. The key is to recognized species that are presumed to do well under future climatic conditions adapt silvicultural activities around that.

The impacts of climate change on trees, forests and ecosystems increase the level of uncertainty about the response of ecosystems to silvicultural activities. The implementation of adaptive management allows forest managers to make better decisions in the present, gain knowledge and experience of the ecosystems so future management decisions can be improved.

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