Using portfolio theory to improve yield and reduce risk in black spruce family reforestation

By Y. H. WENG[1),*)], K. A. CROWE[2)], W. H. PARKER[2)], D. LINDGREN[3)], M. S. FULLARTON[1)] and K. J. TOSH[1)]

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Abstract

Family forestry, defined as the deployment of families in mixture into plantations, is becoming an attractive option for black spruce (*Picea mariana* (Mill.) BSP) in New Brunswick, Canada. With many elite families of black spruce being available, there is a knowledge gap regarding how to compose a mixture of families that optimally balances the objectives of increased yield and reduced risk. This study, based on real field test data, investigates the application of a model based on the modern portfolio theory to optimally balance yield and risk when selecting a portfolio (mixture) of black spruce families to deploy in reforestation. The risk was expressed as the variance of the family portfolio, an effective indicator of yield stability. This is an innovative approach in forestry and it is compared to the currently used method, truncation-deployment, defined as the equal deployment of seed of selected families. Results show that the portfolio theory searched for the combination of yield and stability and produced family portfolios maximizing yield at a given stability or minimizing yield instability at a given yield. The portfolio theory was never inferior in maximizing yield to the truncation-deployment approach when yield stability is a concern. We recommend using portfolio theory to determine family portfolios for family forestry. While this study targets to family forestry, the results may be relevant to other deployment strategies where stability is a concern, such as clonal forestry.

Key words: family forestry, portfolio theory, yield stability, tree improvement, black spruce.

1. Introduction

Black spruce (*Picea mariana* (Mill.) B.S.P.) is the most important commercial species in New Brunswick (NB), Canada, where about 8 million seedlings are planted annually. Due to its economic importance, the New Brunswick Tree Improvement Council (NBTIC) started improvement activities for this species in the early 1970s, using a procedure of seed orchard paired with family testing (FOWLER, 1986). Currently, bulked seed collected from seed orchards is the main source for reforestation in NB (WENG et al., 2010). However, recent realized gain trials for black spruce have demonstrated that the family forestry approach, defined as the deployment of superior half- or full-sib families in a mixture, can produce substantially higher gain over the use of bulked orchard seedlots (WENG et al., 2010; WENG, 2011). Similar results have been obtained for other commercial species including loblolly pine (*Pinus taeda* L.) (MCKEAND et al., 2006) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (ST. CLAIR et al., 2004).

Considering the benefit of family forestry, and since the provincial orchards are producing more seed than are required for current reforestation, a strategy employing harvest and deployment of seedlots selected from the best subset of families (usually the best 15 families) in the orchard, a format of family forestry, has been proposed and practiced in NB since 2011. Specifically, seed are collected from families with breeding values greater than a pre-given value and deployed in an equal proportion (known as the truncation-deployment approach). While this approach is simple in application, it has been demonstrated to be inefficient in maximizing yield (WENG et al., 2012). When a family mixture is planted across multiple environments, its aggregate yield is determined not only by its genetic potential (average breeding value) but also by its yield stability. For truncation-deployment approach, yield stability is not taken into consideration. Thus, an effective selection and deployment approach to balance yield and yield stability is essential for practicing family forestry. The yield stability of a plantation consisting of a family mixture is a result of the stability of each individual family and covariances (or relationships) in yield among families.

Numerous parameters have been proposed and applied to measure yield stability, as reviewed by BECKER and LÉON (1988); yield variance, a static parameter, is believed to be a good indicator (FRANCIS and KANNENBERG, 1978; BECKER and LÉON, 1988; AKCURA and KAYA, 2008; MURPHY et al., 2009), and this is particular true when the testing and deployment environments are similar (BECKER and LÉON, 1988). A family mixture with a relatively large stability variance is believed to have low stability, and thus assumes a high risk in achieving its expected yield. In conventional plant breeding programs, breeders have applied an index selection method to balance yield and yield stability in breeding population selection (LI and MCKEAND, 1989). This method combines yield and yield stability of an individual family into an index and does not take into account covariances between families. Thus, making selections by index selection might not be ideal, at least for family forestry purposes.

The issue of balancing yield and yield stability in current family deployment methods can be addressed through modeling the problem of mixing and deploying families across multiple environments as a portfolio optimization problem. Portfolio theory began with the

[1)] New Brunswick Department of Natural Resources, Kingsclear Forestry Nursery, Island View, NB, Canada E3E 1G3.

[2)] Faculty of Natural Resources Management, Lakehead University, 955 Oliver Road, Thunder Bay, ON, Canada P7B 5E1.

[3)] Department of Forest Genetics and Plant Physiology, Swedish University of Agriculture Science, SE-901 83 Umeå, Sweden.

[*)] Corresponding author: Y. H. WENG. E-Mail: Yuhui.weng@gnb.ca

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publication of MARKOWITZ' (1952) seminal paper on the topic in which he, for the first time, offered a formula by which the risk of a portfolio can be measured by the sum of the variability of its parts. The purpose of using variance as a measure of risk is that it indicates the diversity of a portfolio. In other words, if all of the assets (families) in a portfolio (mixture) varied identically over time (or environments), then the diversity of the portfolio would be low, and its risk is high. Hence, a portfolio which minimizes both variance and covariance minimizes risk. For these reasons, we believe that the portfolio approach may be a useful way to address the current oversights in current family deployment methods noted above.

An application of the portfolio theory to select deployment populations in forestry was first utilized by CROWE and PARKER (2008). They found that portfolio theory was an effective tool to optimize seed source selections in order to maximize adaptation and reduce risk by minimizing covariance under various predicted climate change scenarios. Further biological applications of portfolio theory to select rice and wheat variety mixtures optimizing yield and yield stability have resulted in substantial improvements of yield stability with associated financial benefits (NALLEY et al., 2009; BARKLEY et al., 2010).

With increasing interest in family forestry for black spruce in NB, the problem of selecting a portfolio of families that to maximize yield and yield stability is a pressing research problem. The goal of this study was to investigate the applicability of the portfolio theory to assess yield stability when applied to family forestry by applying this approach to two candidate family sets taken from already established family tests of NB's black spruce tree improvement programs. Parallel results applying truncation-deployment approach were also determined and used as the reference for comparison.

2. Materials

Two candidate family sets were used in this study. The first set was derived from a first generation black spruce progeny test (NBTIC, 1991), hereafter referred to as Set_{1_HS}. The test was established in 1991 at five locations across NB. The test consisted of 79 unrelated half-sib families using a randomized complete block design (RCBD) of 15 blocks and two-tree row plots. In 2005, individual tree height and diameter at breast height were measured, and individual tree volumes were calculated using methods established by HONER et al. (1983) and multiplied by 1,000 (converting to dm^3) so that volumes were large enough to carry sufficient digits. Family breeding values of volume were predicted using best linear unbiased prediction (BLUP), and the top 12 families were used as the candidate families of Set_{1_HS}.

The second set was selected from a second-generation black spruce full-sib progeny test (NBTIC, 2000), referred to as Set_{2_FS} hereafter. The test was planted at five locations across NB in 2000 using a RCBD of 8

Table 1. – Summary statistics (yield in dm^3 for Set_{1_HS} and in m for Set_{2_FS} and variance (v)) for the candidate families by set and sampling examples of family proportions under a constant yield (24.52 dm^3 for Set_{1_HS} and 3.82 m for Set_{2_FS}) by truncation-deployment (T) and portfolio theory analysis (P).

Set_{1_HS}					Set_{2_FS}				
	Summary		Example			Summary		Example	
Family	Yield	v	T	P	Family	Yield	v	T	P
F22	25.833	147.28	0.250	0.387	F1073	3.845	0.629	0.250	0.193
F10	24.523	123.15	0.250	0.081	F1018	3.838	0.473	0.250	0.466
F75	24.177	114.71	0.250	0.281	F1066	3.830	0.688	0.250	0.094
F31	23.543	119.57	0.250	0.000	F1104	3.785	0.401	0.250	0.098
F70	23.453	110.74	0.000	0.000	F1022	3.767	0.679	0.000	0.000
F81	23.393	146.49	0.000	0.000	F1024	3.766	0.753	0.000	0.019
F21	23.327	100.63	0.000	0.013	F1096	3.765	0.770	0.000	0.000
F63	23.176	91.88	0.000	0.103	F1020	3.753	0.657	0.000	0.054
F25	22.764	106.56	0.000	0.000	F1048	3.737	0.583	0.000	0.076
F82	22.610	92.10	0.000	0.134	F1062	3.725	0.605	0.000	0.000
F23	22.578	102.63	0.000	0.000					
F02	22.474	88.35	0.000	0.000					
Z^a			53.55	42.25				0.338	0.292

[a] Stability variance.

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replications and 4-tree row plots. A total of 89 full-sib families were included in the test. These families were created by pair-mating between parent trees selected from the first-generation progeny tests. In 2010, 10-yr-old tree height was measured. Family genetic values of height were predicted using the BLUP, and the top 10 families were used as the candidate families for deployment. Surprisingly, all these families were genetically unrelated, i.e., no common mother or father, except two which shared a common father.

Table 1 lists all the candidate families of each set, sorted by decreasing yield. Fifteen-year individual tree volume (dm^3) and 10-year height (m) were used as the yield for the Set_{1_HS} and $Set_{2\_FS,}$ respectively. Overall these families represent the ones which might be utilized in family forestry in NB.

3. Methods

Yield and yield variance across locations of each candidate family, and the pair-wise phenotypic covariances between two families for each of the two test sets were calculated using the SAS MEAN procedure (SAS INSTITUTE, 1990).

Our objective was to reduce yield instability, expressed as yield variance (Z), at a preset yield by selecting optimal family portfolios consisting of n families from each of the two candidate family sets. The plantation yield (λ) from deploying either family portfolio is a function of the decision variable (x_i) *i.e.*, the fractional contribution of the ith family to the portfolio, and that family's yield (y_i):

$$\lambda = \sum_{i=1}^{n} x_i y_i \qquad [1]$$

The 'stability variance (Z)' of the portfolio is the sum of covariances between families (c_{ij}):

$$Z = \sum_{i=1}^{n}\sum_{j=1}^{n} x_i x_j c_{ij} \qquad [2]$$

Since the formula [2] includes all pairs of families, those pairs where i equals to j represent covariance between identical families, is equal to variance of the family i (v_i). Thus, the equation [2] can be further expressed as

$$Z = \sum_{i=1}^{n}\sum_{j=1}^{n} x_i x_j c_{ij} = \sum_{i=1}^{n} x_i v_i + 2\sum_{i=1}^{n}\sum_{j=i+1}^{n} x_i x_j c_{ij} \qquad [3]$$

In order to reduce instability at a given yield, the model used is formulated as follows:

$$\text{Minimize } Z = \sum_{i=1}^{n}\sum_{j=1}^{n} x_i x_j c_{ij} = \sum_{i=1}^{n} x_i v_i + 2\sum_{i=1}^{n}\sum_{j=i+1}^{n} x_i x_j c_{ij} \qquad [4]$$

Subject to

$$\sum_{i=1}^{n} x_i y_i = \lambda \qquad [5]$$

$$0.0 \le x_i \le 1.0 \qquad \text{for each } i \qquad [6]$$

$$\sum_{i=1}^{n} x_i = 1 \qquad \text{for each } i \qquad [7]$$

Equation [6] ensures that each proportion of a family selected to make up a portfolio must be greater than or equal to zero and less than or equal to 1. Equation [7] ensures that all proportions selected must sum to one.

For comparison purposes, yield and stability variance were also calculated for truncation-deployment method. A truncation value was first determined and the selected families were deployed equally (equal x_i). Stability variance values (Z) were then determined using equation [2].

4. Results

Table 1 presents the yield and variance by set and candidate family. As expected, the difference in yield among families was not substantial, ranging from 22.474 to 25.833 dm^3 volume per tree for the Set_{1_HS} and from 3.725 to 3.845 m for the Set_{2_FS}. The corresponding single-family variances ranged from 88.35 to 147.28 and from 0.401 to 0.770, respectively. The association between yield and variance was strong for the Set_{1_HS} with a correlation coefficient of 0.74 but was negatively weak for the Set_{2_FS} with a coefficient of –0.25. The between-family covariance varied greatly ranging from -12.41 to 76.42 with an average of 31.99 for the Set_{1_HS} (*Appendix 1*), and from 0.07 to 0.38 with an average of 0.25 for the Set_{2_FS} (*Appendix 2*). Negative covariances were found only between F22 and F75 (–6.11), between F22 and F82 (–2.10) and between F63 and F82 (–12.41) in the Set_{1_HS}.

Figure 1 presents the results of using portfolio theory to minimize Z at a given yield. Deployment of the highest-yield families (100% F22 for the Set_{1_HS} and 100% F1073 for the Set_{2_FS}, respectively) formed the highest yield points (25.833 dm^3 and 3.845 m) on the respective efficient frontier, with stability variance equal to single family variances of 147.28 and 0.629, respectively. The tradeoff between yield and stability variance resulted in increasingly efficient portfolios. As expected, the higher yield was associated with lower stability (higher Z). For the Set_{1_HS}, the single-source yield of 25.833 decreased to 23.488 dm^3 for the optimal portfolio with a corresponding decrease in stability variance from 147.28 to 29.05 (*Figure 1a*). Similarly for the Set_{2_FS}, when the required yield decreased from 3.845 to 3.781 m, the corresponding stability variance decreased from 0.629 to 0.240 (*Figure 1b*). It can also be seen from *Table 1* and *Figure 1* that single-family deployments for each set (where $Z = v_i$) produced different combinations of yield with stability variance always greater than for an optimized portfolio.

Alternative portfolios were developed to compare the truncation-deployment to the portfolio theory approach (*Figure 1*). There is a definite trade-off between yield and yield stability regardless of which of the two methods is used. To maximize yield, both methods sampled the single top family of either data set resulting in the same and maximum stability variance values. However, the superiority of the portfolio approach becomes apparent as yield demands are relaxed to obtain greater yield stability. To attain the yield of 23.488 dm^3 for the Set_{1_HS}, the stability variance for truncation-deployment was 33% greater than for the portfolio approach raising

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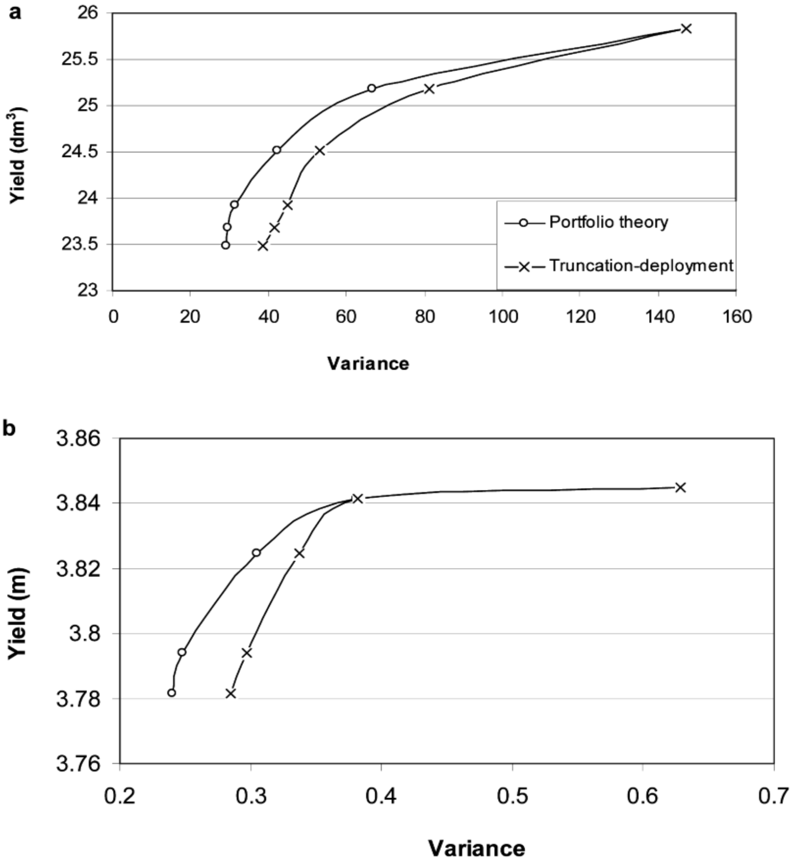

Figure 1. – Tradeoff between yield and stability variance of family portfolios developed by portfolio theory and truncation-deployment based on: (a) Set_{1_HF} and (b) Set_{2_FS}.

from 29.05 to 38.54 (*Figure 1a*). Likewise, to attain the yield of 3.781 m by truncation-deployment for the Set_{2_FS}, the stability variance increased by 19% from 0.240 to 0.285 (*Figure 1b*). The superiority of portfolio theory was also demonstrated by maximizing yield at a given variance; when holding the variance of 38.54 as the constant for the Set_{1_HS}, the portfolio theory produced a 4.2% higher yield than the truncation-deployment. It is also apparent from the shape of the efficient frontier curves for both datasets in *Figure 1* that there is a lower limit to the reduction of stability variance. Seed source portfolios midway (45° tangent to curve) on the efficient frontier may represent the best trade-off between yield and risk. Results also showed that the superiority of the portfolio theory over the truncation-deployment was less significant for Set_{2_FS} than for Set_{1_HS}. Its poor association between yield and variance (= –0.25) may explain the relatively low superiority of the portfolio theory.

Table 1 presents an example of how each method sampled a family portfolio for a specified yield of 24.52 dm^3 for Set_{1_HS} and of 3.82 m for Set_{2_FS}. The truncation-deployment method sampled families by rank order of their yield. However, the portfolio theory method limited the contribution of families of larger variance and deployed more negatively or less related families, as a result, it deployed a greater proportion of families of small variance (F63 and F82 in the Set_{1_HS} and F1018 and F1104 in the Set_{2_FS}) or of negatively correlated (F82 in the Set_{1_HS}). As expected, stability variance was much reduced by the portfolio theory approach. Compared to the truncation-deployment, the stability variance (Z) was reduced by 26.7% for Set_{1_HS} and by 15.8% for Set_{2_FS} when the portfolio method was applied.

5. Discussion

Multi-site realized gain tests in NB have demonstrated that family forestry for black spruce can substantially improve plantation productivity over the conventional planting of seedlots from seed orchards of mixed cone collection (Weng et al., 2010; Weng, 2011). For either procedure, an important decision is how to effectively combine families for deployment across a variety of soil types and local climate regimes. While many issues need to be considered, maximizing yield and minimizing risk, *i.e.* maximizing yield stability, are key needs that have been largely neglected in forestry practice. To this goal, actual field trial results determining both yield and stability are presented based on the portfolio theory approach. Through selection of individual families and varying their proportions, the portfolio theory method allows companies to plant optimal family portfolios according to balanced stability and yield objectives.

The portfolio theory approach to determining family mixtures is flexible in its application, and the interpretation of results is straightforward. By utilizing information in family yield and yield stability, portfolio theo-

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ry evaluates all feasible family combinations under the constraints and finds the optimal solution that maximizes or minimizes the target value. A family portfolio that has negative or small covariate yields will result in a more stable aggregate yield for the entire plantation than specialized strategies of planting a single family, and a family that is at risk in terms of its own yield variance may still be attractive if its yield is poorly correlated with yields of other families in the mixture (*Table 1*). Obtained optimal portfolios can be presented as the efficient frontier (*Figure 1*) to reflect the trade-off between stability and yield. Any family mix not located on the frontier can be considered inefficient in the sense that yield could be maintained with more stability variance (*e.g.* by deploying fewer higher yielding families at higher risk) or vice versa. Some companies are risk averse and would rather obtain a guaranteed yield level while others like to take on slightly more risk for a higher profit. The risk appetite of the companies will determine the optimal portfolio to use. From a practical point of view, deploying very low proportions can be annoying and difficult to manage and may be uneconomical and only very marginally improve the deployment solutions. Thus, in practice, low deployment proportions could instead be set to zero, at least for family forestry purposes.

The application of real test data demonstrated that the portfolio theory could produce considerable improvements in yield or stability without any sacrifice in stability or yield relative to truncation-deployment (*Figure 1*). The basic difference between the truncation-deployment approach and the portfolio theory method is that the former considers the yield values only, whereas the latter searches for the combination of yield and stability to maximize yield or minimize risk. The portfolio theory approach optimizes the proportions and favors less sampling of families with higher variance (*Table 1*).

Application of portfolio theory to family forestry needs information of individual family variances and between-family covariances, as described in the equation [3]. While family variances can be obtained from multiple-sites tests easily, estimating covariances is more complicated and needs data from complicated experimental designs (EULER et al., 1992; FOSTER et al., 1998). These designs are necessary because between-family covariance is affected by many factors, in particular, the inter-family competition and family responses to site conditions. Families planted in a typical genetic test, such as tests used in this study, have limited chances to be adjacent to each other; thus, estimated covariances due to inter-family competition may be underestimated. Research on inter-genotypic competition has seldom been done and only three papers have been published. All these studies suggest that inter-genotypic competition played an important role in stand growth (EULER et al., 1992; FOSTER et al., 1998; STAUDHAMMER et al., 2009). As shown in this study, applying portfolio theory method to family forestry is of especially effective when the inter-family covariances are substantial.

Application of portfolio theory to genetic selection decisions has not been widely reported. Benefits were significant when applying portfolio theory to decision-making in animal selection (SCHNEEBERGER et al., 1982; SMITH and HAMMOND, 1987). More recently, this tool has been applied to agriculture and forestry. By holding the actual yield of 2007 as a constant, NALLEY et al. (2009) reported that selecting rice varieties using portfolio theory reduced variance by 16 to 71%, resulting in an increased profit per hectare from 3 to 26% in Arkansas Delta. Based on historical test plot data, BARKLEY et al. (2010) illustrated how portfolio theory could reduce risk and increase yields for Kansas wheat farmers. In forestry, CROWE and PARKER (2008) demonstrated how the portfolio theory could be used to select an optimal set of seed sources to minimize risk and maximize return (adaptivity) in an environment of deep uncertainty regarding future climate scenarios. All of the above studies, together with the current study, suggest that portfolio theory could be an excellent tool in seedlot selection decisions to improve yield and reduce risk.

The families of the two data sets used in this study were genetically unrelated, except two which share a common father in the second set. However, current family forestry approaches are usually based on materials from advanced breeding cycles, and the elite families are more or less genetically related. To reduce risk due to unpredictable biotic or environmental stresses, operationally, it is always ideal to set a minimum acceptable population size for a deployment mixture (LINDGREN, 1993). Toward this end, other unequal deployment approaches (such as linear deployment and optimal deployment) have been proposed to form family portfolios. While both conceptually similar to the portfolio theory selection, these approaches target to maximize yield at an acceptable diversity level (LINDGREN and MATHESON, 1986; LINDGREN and MULLIN, 1997). The portfolio theory approach optimizes yield stability, not mixture diversity, which may limit its application when a diversity level is required for a deployment population. However, closely-related families are likely to have similar growth rates and concurrent demands, causing a large between-family covariance, and are less likely chosen by the portfolio theory approach. When relatedness is an issue, the diversity level of a mixture selected by the portfolio theory can be manipulated by setting a minimum and/or a maximum proportion for family contribution, i.e. by setting the equation [6] to $0.05 \le x_i \le 0.2$ for all i, where the minimum is 5% and the maximum is 20%. However, such a restriction may produce sub-optimal results.

This paper showed the advantages of portfolio theory when yield stability is a constraint. With many choices of selection and deployment combinations, it is necessary to clearly understand the goals to be achieved before contemplating available choices. While effective population size and variance both are indicator of diversity, variance represents yield stability but effective population size is a genetic concept about pedigree relationships and is an especially good indicator of population inbreeding. When inbreeding is a concern, such as selection for seed orchard establishment and breeding populations, linear or optimal deployment is the preferred method. Portfolio theory method is a more effective tool when yield stability is a concern. Family-by-location interaction also plays important role in forming family portfolios. If the inter-

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action is significant and results in substantial ranking changes, selecting and deploying different family mixtures to different sites to maximize family response to site conditions should be applied. A significant and large family-by-location interaction, however, would indicate that breeding zones were poorly defined. Portfolio theory selection seems suitable when the significant family-by-location interaction is mainly due to scale effects. This is always the case in NB. New Brunswick is small geographically (72,908 km^2 in total), and the whole province is designed as one breeding/seed zone (FOWLER, 1986). Data analyses on large scale genetic tests planted across NB have shown that significant ranking changes among families have rarely been observed but site-to-site variation in yield is substantial among families and common. As shown in this study, incorporating stability into family selection using portfolio theory will greatly increase plantation productivity with less risk. Application of the portfolio theory selection may be also suitable under the following situations. First, when a breeding program includes multiple breeding populations with each having various breeding targets (i.e., disease resistance, drought resistance, wood quality, growth, etc.), portfolio theory has a stronger ability to combine families of inverse yield responses to growing conditions. Second, when yield and variability of candidate families are strongly and positively correlated, portfolio theory sets more restrictions on top families to minimize the portfolio's variance. In this study, the Set_{2_FS} had a negative (=–0.25) while Set_{1_HS} showed a strong and positive (=0.74) relationship between yield and variability. This is why the portfolio theory selection was relatively higher efficiency in the Set_{1_HS} than in the Set_{2_FS}. Finally, when considering the possible environmental uncertainties in the future, the portfolio theory has the greater potential to optimize seedlot combinations to minimize maladaptation (CROWE and PARKER, 2008).

6. Conclusion

In conclusion, this study used portfolio theory analysis to find yield- and stability-maximizing combinations of black spruce families for family forestry. Results were encouraging; the portfolio theory method is well suited to this end because the portfolio theory optimizes family combinations by extending the analysis to include not only yield but also yield variability. The application of real field test data demonstrated that, when yield stability is a concern, the portfolio theory was never inferior to the truncation-deployment. Overall, the portfolio theory could produce family portfolios with higher yield at a given stability or with lower risk at a given yield than the truncation-deployment. While this study targets family forestry, the results are also relevant to other deployment strategies where stability is a concern, such as clonal forestry.

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Appendix 1. – Family variances and between-family covariances of 15-yr individual tree volume for the Set_{1_HS}.

Family	F22	F10	F75	F31	F70	F81	F21	F63	F25	F82	F23	F02
F22	147.28	27.339	-6.108	38.616	31.415	62.573	20.087	23.382	38.209	-2.096	44.137	31.712
F10	27.339	123.15	50.276	34.341	23.939	51.309	35.067	29.785	44.562	30.566	38.674	19.402
F75	-6.108	50.276	114.70	30.332	34.487	44.074	27.719	16.426	32.283	12.437	8.4632	43.389
F31	38.616	34.341	30.332	119.56	63.401	46.983	25.887	34.065	76.417	12.173	32.236	23.434
F70	31.415	23.939	34.487	63.401	110.73	48.780	22.590	41.054	68.218	35.649	28.784	34.916
F81	62.573	51.309	44.074	46.983	48.780	146.49	40.916	32.369	38.731	26.483	35.926	57.566
F21	20.087	35.067	27.719	25.887	22.590	40.916	100.63	25.289	51.258	28.785	16.361	34.605
F63	23.382	29.785	16.426	34.065	41.054	32.369	25.289	91.883	32.257	-12.41	26.316	32.436
F25	38.209	44.562	32.283	76.417	68.218	38.731	51.258	32.257	106.56	28.829	32.942	23.675
F82	-2.096	30.566	12.437	12.173	35.649	26.483	28.785	-12.41	28.829	92.104	17.792	6.4049
F23	44.137	38.674	8.4632	32.236	28.784	35.926	16.361	26.316	32.942	17.792	102.63	23.711
F02	31.712	19.402	43.389	23.434	34.916	57.566	34.605	32.436	23.675	6.4049	23.711	88.354

Appendix 2. – Family variances and between-family covariances of 10-yr individual tree height for the Set_{2_FS}.

Family	F1073	F1018	F1066	F1104	F1022	F1024	F1096	F1020	F1048	F1062
F1073	0.629	0.213	0.330	0.351	0.263	0.245	0.312	0.277	0.211	0.175
F1018	0.213	0.473	0.197	0.165	0.251	0.211	0.199	0.123	0.085	0.199
F1066	0.330	0.197	0.688	0.342	0.305	0.275	0.300	0.342	0.363	0.339
F1104	0.351	0.165	0.342	0.400	0.235	0.186	0.317	0.243	0.246	0.160
F1022	0.263	0.251	0.305	0.235	0.679	0.133	0.359	0.225	0.270	0.362
F1024	0.245	0.211	0.275	0.186	0.133	0.753	0.120	0.074	0.274	0.176
F1096	0.312	0.199	0.300	0.317	0.359	0.120	0.770	0.384	0.316	0.360
F1020	0.277	0.123	0.342	0.243	0.225	0.074	0.384	0.657	0.131	0.274
F1048	0.211	0.085	0.363	0.246	0.270	0.274	0.316	0.131	0.583	0.180
F1062	0.175	0.199	0.339	0.160	0.362	0.176	0.360	0.274	0.180	0.605

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