Budbreak and Winter Injury in Exotic Firs

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Abstract. Seventeen Abies species were evaluated for budbreak and frost injury at four locations in Michigan. Freeze tests were conducted on four species growing at the Horticulture Teaching and Research Center to determine cold hardiness levels during winter. Species differed (P < 0.0001) in their days to budbreak at all locations. Trees that had broken bud were more prone to late spring frost damage than trees yet to break bud. Species differed in chlorophyll fluorescence, bud damage, and needle damage after exposure to –44 °C. Bud, foliage, and cambium damage were correlated with chlorophyll fluorescence following freeze tests. Budbreak and midwinter cold hardiness were correlated. Species breaking bud earlier displayed greater midwinter cold hardiness than species breaking bud later. Selection criteria for future Abies introductions to the upper midwestern U.S. should include identifying species with late budbreak to reduce risk of late frost injury.

Materials and Methods

Site locations. More than 1100 trees representing 38 species and hybrids of Abies were part of a true fir species trial initiated at the Kellogg Research Forest (KRF), Augusta, Mich., in early 1991. In 2002 and 2003, about 300 trees representing 17 species and hybrids (Table 1) were transplanted to three locations in Michigan: Clarksville Horticulture Experiment Station, Clarksville (CHES); Horticulture Teaching and Research Center, East Lansing (HTRC); and Northwest Michigan Horticulture Research Station, Traverse City (NWHRS) (Fig. 1). These three locations along with the KRF represent different climate regions (Table 2) in Michigan. Soils at HTRC and NWHRS were loamy sand while soils at CHES and KRF were sandy loam. Trees were dug and balled and burlapped at 60 to 76 cm root balls in accordance with nursery standards. At least four trees of each species or hybrid were planted at each location with the exception of the HTRC where one to four additional trees of each species were planted when available. Trees were planted at about 4.5 m intervals in a complete randomized design at each location. In addition, at KRF four trees of each species were selected for further study.

Fertilization. In Spring 2004, sites were fertilized with granular 21–0–0 ammonium sulfate at a rate of about 133 g per tree, to lower soil...
**Table 1. List of Abies species planted at four locations in Michigan.**

| Common name                      | Scientific name            | Geographic origin | Elevation (m) | Latitude (°N) |
|----------------------------------|----------------------------|-------------------|---------------|---------------|
| Ernst fir                        | *A. chensiensis* Van Tiegh. | Asia              | 2500–3800     | 25–33         |
| Korean fir                       | *A. koreana* Wils.         | Asia              | 1000–2000     | 33–36         |
| Needle fir                       | *A. holophylla* Maxim.     | Asia              | 0–1400        | 33–49         |
| Nikko fir                        | *A. homolepis* Sieb. et Zucc. | Asia            | 600–2200      | 33–38         |
| Siberian White fir               | *A. nephrolepis* (Trautv.) Maxim. | Asia          | 500–2000      | 35–55         |
| Veitch fir                       | *A. veitchii* Lindl.       | Asia              | 1200–3000     | 33–36         |
| Balsam fir                       | *A. balsamea* (Linn.) Mill. | N. America        | 0–1500        | 38–59         |
| Cannan fir                       | *A. balsamea* var. phanerolepis (Fern.) Liu | N. America | 0–1500        | 38–59         |
| Corkbark fir                     | *A. lasiocarpa* var. arizonica (Merr.) Lemm. | N. America | 0–1700        | 37–39         |
| Fraser fir                       | *A. fraseri* (Pursh.) Poir. | N. America        | 1100–2100     | 35–37         |
| Noble fir                        | *A. procera* Rehd.         | N. America        | 100–2700      | 41–48         |
| Subalpine fir                    | *A. lasiocarpa* (Hook.) Nutt. | N. America | 0–3500        | 32–64         |
| Nordman fir                      | *A. nordmanniana* (Steven) Spach. | Mediterranean | 1000–2200     | 40–44         |
| Turkish fir                      | *A nordmanniana* ssp. equi-trojani (Aschers. et Sint. Ex Boiss.) | Mediterranean | 1000–2200     | 40–44         |
| Fraser × Nikko hybrid            | *A. fraseri* × *homolepis* | N. America/Asia   | ---           | ---           |
| Korean × Balsam hybrid           | *A. koreana* × *balsamea*   | N. America/Asia   | ---           | ---           |
| Korean × Veitch hybrid           | *A. koreana* × *veitchii*   | Asia/Asia         | ---           | ---           |

*Referenced in Liu, 1971.

pH, and insure that nitrogen was not limiting. Fertilizer was applied at CHES on 29 Apr., at HTRC on 22 Apr., and at NWHRS on 11 May. On 7 July 2004, 46–0–0 urea was applied at CHES at a rate of 91 g per tree. Trees at KRF were fertilized every fall with 21–0–0 at 85 g per tree. Trees exceeding 0.9 m received 28 g of fertilizer for each additional 0.3 m in height.

**Budbreak.** Beginning 16 Mar. 2004 and 24 Mar. 2005, trees at each of the three outlying sites and the KRF were surveyed for budbreak, considered to have occurred once one shoot broke its bud scale. Trees were inspected weekly until all trees at each location had broken bud. Air temperature was recorded using weather stations located at each site and available for download on the Michigan Automated Weather Network (MAWN) (http://www.agweather.geo.msu.edu/mawn/) website. For each inspection date, growing degree days (GDD) were calculated using a base temperature of 10 °C (Dickson et al., 2000) and the numerical integration method using the MAWN website.

**Frost damage.** Temperatures reached –2.2 and –2.4 °C on 3 and 4 May 2004 at the KRF after some trees had begun to break bud. Trees were visually rated on 5 May 2004 using the following 0 to 4 scale: 0 = no shoots damaged, 1 = 1% to 25%, 2 = 26% to 50%, 3 = 51% to 75%, and 4 = 76% to 100% of shoots damaged. Shoots were considered damaged if they were brown in color or had lost rigidity. All trees in each species block (n = 7 to 42) were inspected for frost damage, in addition to the four individuals previously selected at random for the budbreak study.

**Cold hardness.** Four species were chosen to measure cold hardiness and represent species with early, early-mid, mid-late, and late budbreak groups respectively: *A. nephrolepis*, *A. balsamea* var. *phanerolepis*, *A. chensiensis*, and *A. veitchii*. Shoots from the current year’s growth were collected from three trees of each species at the HTRC. Samples were collected on 13 Dec. 2004, 24 Jan. 2005, and 7 Mar. 2005 with freeze tests beginning 1 to 3 d later. Twelve samples for each temperature (4 species × 3 replications) treatment were placed on moist cheese cloth, covered with aluminum foil, and rolled into bundles. A thermocouple was inserted into the stem of one sample in each bundle to measure stem temperature. Bundles were then placed into a freezer (SciTemp, Adrian, Mich.) and stored at 2 °C until the test began. Temperatures were lowered at 3 °C·h⁻¹ and a bundle was removed at each targeted temperature until completion of the run. A control bundle was kept in a walk-in cooler at 2 °C where bundles were allowed to thaw following removal from the freezer.

In the 13 Dec. 2004 and 24 Jan. 2005 tests, a bundle was removed at each of the following temperatures: 2, –6, –9, –12, –15, –18, –21, –24, –27, –30, –33, –36, –39, –42, and –44 °C. In the 7 Mar. 2005 test, a bundle was removed at the following temperatures: 2, –6, –9, –12, –15, –18, –21, –24, –27, –30, –33, –36, –39, –42, and –44 °C. Bundles were placed in a walk-in cooler and allowed to thaw at 2 °C for 2 to 3 d and then placed in a high humidity chamber at room temperature (25 °C) for 4 to 5 d. Then samples were visually rated for needle damage, bud damage, and cambium damage using the following 0 to 2 scale: 0 = no damage; 1 = partial browning of the tissue; 2 = dead tissue.

Chlorophyll fluorescence (F₀/Fₘ) was measured using two needles from every sample in each temperature treatment using a portable

![Fig. 1.Location of four Abies trials in Michigan: 1) Kellogg Research Forest (KRF), 2) Clarksville Horticultural Experiment Station (CHES), 3) Horticulture Teaching and Research Center (HTRC), and 4) Northwest Michigan Horticultural Research Station (NWHRS).](image-url)
chlorophyll fluorescence system (plant efficiency analyzer, Hansatech Instruments Ltd., Norfolk, U.K.). Samples were clipped and dark-acclimated for 15 min before readings were taken.

Statistical analysis. Species effects on budbreak and cold hardiness damage were determined using PROC MIXED (SAS Inc., Cary, N.C.). When significant differences were indicated, means were separated using Tukey’s Studentized range test (Sexton, 1998). Species and year effects on the GDD required to budbreak were determined using PROC GLM (SAS Inc.) and means were separated using the Tukey’s Studentized range test. Species and test effects on the date of budbreak and GDD required for budbreak were determined by analysis of variance using a fixed effects model:

\[ y_{ijk} = \mu + \alpha_i + \gamma_j + \varepsilon_{ijk} \]

where \( y_{ijk} \) = response of the tree, \( \alpha_i \) is the effect of species \( i \), \( \gamma_j \) is the effect of the location \( j \), and \( \varepsilon_{ijk} \) is the error term. Damage ratings were analyzed using non-parametric measures and with a pairwise comparison of means using the Kruskal-Wallis test (Ott, 1988). Correlation between tissue damage, \( F_v/F_m \), and the mean date of budbreak were identified using PROC CORR (SAS Inc.).

Results

Budbreak. The date of budbreak varied with planting location (\( P \leq 0.0001 \)), species (\( P \leq 0.0001 \)), and year (\( P \leq 0.03 \)) (Table 3). We observed variation in budbreak within individual trees as not all buds broke at the same time on a given tree. Budbreak in mid to late April in both years, lasting between 29 to 49 d in 2004 and 36 to 49 d in 2005 depending upon location. Trees at southern sites began and finished breaking bud earlier than northern sites. All trees had broken bud by 17 June 2004 and 9 June 2005. In both years, A. holophylla, A. lasiocarpa, A. lasiocarpa var. arizonica, and A. nephrolepis were among the first species to bud break. There is some evidence that A. veitchii and A. holophylla, although several species were in the last group to break bud at KRF. In 2005, the species broke bud earlier than A. balsamea at least at three locations: A. holophylla, A. lasiocarpa, A. lasiocarpa var. arizonica, and A. nephrolepis. At KRF in 2004, trees breaking bud after A. balsamea showed no evidence of frost damage with the exception of A. homolepis and A. veitchii. Damage in these two species was limited to trees located on top of a hill which received more thermal time and had already broken bud. As a result, they were damaged by late spring frost while trees growing at the base of the hill had not yet broke bud and thus showed no signs of damage.

Growing degree days (GDD) required for budbreak differed among species (\( P \leq 0.0001 \)), locations (\( P \leq 0.0001 \)), and years (\( P \leq 0.04 \)). Trees at the southern locations accumulated GDD faster and required more GDD for budbreak than at northern locations (Table 4). Growing degree day (GDD) accumulation was initially slower in 2005 but by early June GDD accumulation was nearly equal to 2004. Fewer GDD were required at NWHRS for budbreak than at the other locations.

Species were ranked for budbreak at each location and a strong local location: location correlation existed (Table 5) signifying budbreak among species was generally related at each location. Location x species interaction for both days to budbreak and GDD was significant (\( P \leq 0.0001 \)), indicating the rank order of some species changed among locations. For example, A. koreana was in the last group to break bud at CHES, HTRC, and NWHRS while being one of the first species to break bud at KRF. In A. koreana x veitchii and A. fraseri x homolepis, budbreak was not closely related to the parent species, while budbreak for A. koreana x balsamea was similar to its parents’. Mean days to budbreak at the HTRC was correlated (\( R^2 = 0.38, P = 0.033 \)) with average \( F_v/F_m \) at -44°C (Fig. 2). Trees breaking bud earlier had higher \( F_v/F_m \) values than trees breaking bud later. Abies chensiensis had the lowest \( F_v/F_m \) of the species included in the cold hardiness study.

Late frost damage. Late frost damage following the May 2004 freeze was related to the date of budbreak. Trees breaking bud early had more damage from the late spring frost than those breaking bud later (\( P = 0.798, P < 0.01 \)). At KRF A. holophylla, A. lasiocarpa, A. lasiocarpa var. arizonica, and A. nephrolepis displayed a high percent of frost damage in a large number of trees (Fig. 3). In contrast, A. chensiensis, A. fraseri x homolepis, A. koreana, A. nordmanniana ssp. equi-trojani, and A. procer a displayed no frost damage. At the time of frost, the following species had not completed budbreak: A. fraseri x homolepis, A. homolepis, A. koreana, A. koreana x balsamea, A. procer a, and A. veitchii. In both A. homolepis and A. veitchii late frost damage occurred in some trees not included in the budbreak survey but inspected for late frost damage.

Cold hardiness. Cold hardiness varied among species and by test date. Chlorophyll fluorescence values declined with decreasing temperatures (\( P < 0.001 \)). Chlorophyll fluorescence (\( F_v/F_m \)) values increased as temperatures were lowered during controlled freeze tests in A. chensiensis and A. veitchii but remained constant in A. balsamea var. phanerolepis and A. nephrolepis as temperatures reached -44°C. At -44°C, F_v/F_m differed among species for tests during December 2004 (\( P < 0.002 \)) and January 2005 (\( P < 0.001 \)), but not March 2005 (\( P = 0.10 \)) (Table 6). Needle damage differed among species at -44°C in all tests (\( P < 0.05 \)). Needle damage was greatest in A. chensiensis in all tests. Visible damage to needles, stem tissue, and buds was highly correlated (\( P < 0.001 \)) with a decline in \( F_v/F_m \) values (Table 7). Damage to stem tissue and buds did not differ (\( P > 0.05 \)) among species on any test date. Damage to needles, stem tissue, and buds were highly correlated (\( P < 0.001 \)) with a decline in \( F_v/F_m \) values (Table 7).

Table 2. Thirty-year climate summary and USDA plant hardiness zones for four Abies planting sites in Michigan.

| Location | Avg January low (°C) | Avg July high (°C) | Avg annual precipitation (cm) | Avg annual snowfall (cm) | Growing season (days) | USDA hardiness zone |
|----------|----------------------|--------------------|-------------------------------|--------------------------|-----------------------|-------------------|
| CHES     | -10                  | 28                 | 90.7                          | 145                      | 147                   | 5B                |
| HTRC     | -11                  | 28                 | 78.5                          | 99                       | 150                   | 5A                |
| KRF      | -9                   | 28                 | 89.4                          | 135                      | 149                   | 5B                |
| NWHRS    | -10                  | 27                 | 85.1                          | 244                      | 135                   | 5B                |

- Illinois Dept. of Nat. Res., 2005.
- USDA Plant Hardiness Map, 1990.
- Clarkeville Horticulture Experiment Station (CHES), Clarkeville, Mich.
- Horticultrue Teaching and Research Center (HTRC), East Lansing, Mich.
- Kellogg Research Forest (KRF), Augusta, Mich.
- Northwest Michigan Horticulture Research Station (NWHRS), Traverse City, Mich.
when the last tree broke bud than at KRF, which perhaps can explain the difference in the GDD required for budbreak. In *P. menziesii* var. *menziesii* (Mirb.) Franc., populations from regions with similar winter temperatures, trees from regions with the largest moisture deficit broke bud earlier than the average (Campbell and Sugano, 1979). This suggests that trees from regions frequented by summer drought break bud early in the spring to complete from regions frequented by summer drought and Sugano, 1979). This suggests that trees species to break bud in this study, are native to regions with similar winter temperatures, trees and cold hardiness levels (Dolnicki and Kraj, 1998; Eiga and Sakai, 1984, 1987, Xie and Ying, 1993). One of the limitations of the current study is that provenance information for each species is unknown. Moreover, it is not known if the parent trees of the hybrids were from the same provenance as the pure species included in this study. For example, the *A. veitchii* parent of the *A. koreana × veitchii* hybrid is not necessarily from the same seed source as the pure *A. veitchii* included in this study, which could explain some of the inconsistencies in the budbreak between the parents and their hybrids. Also, variation within species is not accurately represented because each species is represented by a single provenance.

Chlorophyll fluorescence (F/Fl) was a good indicator of cold injury during controlled freeze tests as F/Fl values declined with decreasing temperatures. These results paralleled increasing needle, stem, and bud damage, which is consistent with previous studies (Adams and Perkins, 1993; Binder and Fielder, 1996). Cold hardiness between different plant organs differs in the temperature at which damage occurs (Sakai, 1982). The temperature where damage occurred was different for buds, stems, and needles. However, damage variables and F/Fl values were strongly correlated suggesting that while the temperatures that damage different organs may vary, relative cold hardiness is related (Table 7).

Many studies show differences in cold hardness among species and provenances (Eiga and Sakai, 1984, 1987; Sakai, 1982; Xie and Ying, 1993). As expected, trees included in the cold hardness study also varied in the temperature at which they displayed damage.

### Table 3. Budbreak date of 17 *Abies* species grown at four locations in Michigan in 2004 and 2005.

| Species                        | 2004          | 2005          |
|-------------------------------|---------------|---------------|
| *Abies nepalpesis*            | April 20 a    | April 20 a    |
| *Abies lasiocarpa var. arizonica* | April 22 a    | April 20 a    |
| *Abies holophylla*            | April 21 a    | April 20 a    |
| *Abies lasiocarpa*            | April 22 a    | April 20 a    |
| *Abies balsamea*              | May 2 ab      | April 24 ab   |
| *Abies koreana × veitchii*    | May 3 ab      | April 24 ab   |
| *Abies bal. var. phanerolpis* | May 5 ab      | April 28 ab   |
| *Abies nordmanniana*          | May 5 ab      | April 27 ab   |
| *Abies koreana × balsamea*    | May 5 ab      | May 3 bcd    |
| *Abies fraseri × homolepis*   | May 12 bc     | May 9 bcd    |
| *Abies procer*                | May 12 bc     | May 8 bcd    |
| *Abies nord. ssp. equi-trojani* | May 12 bc    | May 8 bcd    |
| *Abies chensiensis*           | May 12 bc     | May 8 bcd    |
| *Abies homolepis*             | May 16 c      | May 10 bcd   |
| *Abies fraseri*               | May 24 ab     | May 10 bcd   |
| *Abies koreana*               | May 22 a      | May 24 ab     |
| *Abies veitchii*              | May 22 a      | May 10 bcd   |

*Mean within columns followed by the same letter were not statistically different, α = 0.05. Tukey Studentized range test.

### Table 4. Mean growing degree days required before budbreak in 17 *Abies* species grown at four locations in Michigan in 2004 and 2005.

| Species                        | 2004          | 2005          |
|-------------------------------|---------------|---------------|
| *Abies nepalpesis*            | 119 ab        | 153 a         |
| *Abies lasiocarpa var. arizonica* | 124 a        | 148 a         |
| *Abies holophylla*            | 122 ab        | 153 a         |
| *Abies lasiocarpa*            | 170 ab        | 163 ab        |
| *Abies nordmanniana*          | 182 abcd      | 159 a         |
| *Abies bal. var. phanerolpis* | 193 abcd      | 162 ab        |
| *Abies koreana × veitchii*    | 198 abcd      | 170 abcd      |
| *Abies koreana × balsamea*    | 223 abcd      | 218 abcd      |
| *Abies bal. ssp. equi-trojani* | 167 ab      | 158 a         |
| *Abies chensiensis*           | 269 bcdf      | 180 abcd      |
| *Abies homolepis*             | 270 bcdf      | 210 abcd      |
| *Abies procer*                | 272 bcdf      | 223 abcd      |
| *Abies nordmanniana*          | 292 cdg       | 237 abc       |
| *Abies homolepis*             | 317 cdg       | 276 c         |
| *Abies fraseri × homolepis*   | 331 def       | 220 ab        |
| *Abies koreana*               | 347 efg       | 264 bc        |
| *Abies veitchii*              | 364 f         | 266 c         |

*Mean within columns followed by the same letter were not statistically different, α = 0.05.

No records available for trees listed as NR.

Horticulture Teaching and Research Center (HTRC), East Lansing, Mich.

Kellogg Research Forest (KRF), Augusta, Mich.

Northwest Michigan Horticulture Research Station (NWHRs), Traverse City, Mich.

Base temperature 10°C.
to freezing temperatures. One limitation of the current study was the inability of the programmable freezer to be lowered beyond –44 °C. From a practical standpoint, this is near to the lowest annual temperatures in the coldest regions of the upper midwestern U.S. In most years, species showing no signs of damage should be able to survive most winters if given the necessary time to acclimate.

During the fall, the degree of cold hardiness in trees gradually increases, reaches a maximum during midwinter, and gradually declines (Ritchie, 2003). Bud damage in the March test indicates internal development processes related to budbreak may have begun, and warmer temperatures likely reduced cold hardiness levels leading to increased freeze damage. Needle damage ratings were the lowest in January (Table 6). Typically January temperatures were the lowest so more conditioning lead to greater cold hardiness. Increased damage in December and March was likely due to incomplete acclimation and the start of deacclimation leading to less cold hardiness. Stem damage ratings did not differ among species suggesting cambium tissue was adequately insulated at –44 °C, the lowest temperature possible in our controlled freeze test. Chlorophyll fluorescence ($F_v/F_m$) declined progressively between each test suggesting that repairs to cold damage did not begin until growth began again in the spring. Chlorophyll fluorescence ($F_v/F_m$) at –44 °C differed significantly among species in December and January, but not March.

Other factors being equal, trees from colder regions are cold hardy at lower temperatures (Sakai, 1982) and break bud earlier in a common site, due to a reduced chilling and thermal time requirement, than trees from warmer regions. Worral (1983) suggests this may be an adaptation allowing trees to complete their growth before fall frosts in cold regions with short growing seasons. In the present study, date of budbreak and $F_v/F_m$ readings at –44 °C were strongly correlated for the individual trees included in the cold hardness experiment. Trees with maximum cold hardiness levels were among the first species to break bud in the spring while species with reduced cold hardiness were among the last (Fig. 2), suggesting trade-offs between midwinter cold hardiness and the GDD required to break bud.

In summary, species varied in their tolerance of freezing temperatures and in the date they broke bud. Strong correlations existed between the temperatures at which different plant tissues showed visual signs of damage. Species that were among the first to break bud in the spring withstood colder winter temperatures than trees breaking bud later. Species breaking bud early in the spring were more likely to be damaged by late spring frosts. Budbreak should continue as an important selection criterion for conifer species introduced to the landscape and Christmas tree industries in the upper Midwest. Species such as *A. homolepis*, *A. koreana*, and *A. veitchii* were among the last species to break bud at all locations and should be considered for future introduction. Additional studies should focus on identifying provenances with late budbreak and adequate cold hardiness for species with desirable ornamental characteristics such as *A. lasiocarpa*.
Table 6. Mean chlorophyll fluorescence (Fv/Fm) values and needle damage ratings of four Abies species following controlled freeze tests to –44 °C.

| Species               | December  | January  | March  | December  | January  | March  |
|-----------------------|-----------|----------|--------|-----------|----------|--------|
| A. bal. var. phanerolepis | 0.627 a   | 0.657 a  | 0.462  | 1.0 a     | 0.0 a    | 0.3 a  |
| A. nephrolepis         | 0.611 a   | 0.654 a  | 0.705  | 1.0 a     | 0.0 a    | 0.0 a  |
| A. veitchii            | 0.375 a   | 0.492 a  | 0.291  | 1.7 a     | 0.7 a    | 1.7 be |
| A. chensiensis         | 0.022 b   | 0.071 b  | 0.304  | 2.0 b     | 2.0 b    | 2.0 c  |

*Significant at P ≤ 0.05.

Table 7. Pearson’s correlation coefficient for needle, stem, and bud damage and chlorophyll fluorescence (Fv/Fm) in four Abies species growing at the Horticulture Teaching and Research Center in March 2005 following controlled freeze test.

| Needle damage | Stem damage | Bud damage |
|---------------|-------------|------------|
| Fv/Fm         | –0.60***    | –0.69***   |
| Needle damage | 0.77***     | 0.65***    |
| Stem damage   | 0.68***     |            |

*Significant at P ≤ 0.0001.

and A. lasiocarpa var. arizonicana.

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