List of figures, tables, equations, and appendices

CHAPTER 1. PATTERNS OF HOST SUITABILITY AMONG PINE SPECIES

- Fig. 1.1 Resin flow and phloem thickness of red pine, white pine, and jack pine ............ 4
- Fig. 1.2 Densities and reproductive success of Ips in downed trees of three pine species .... 5
- Fig. 1.3 Survival of Ips progeny as a function of attack density in downed trees ............ 5

CHAPTER 2. GROWTH AND ANTI-HERBIVORE DEFENSES OF RED PINE AT ITASCA STATE PARK

- Fig. 2.1 Hypothesized relationship between beetle reproduction and tree resin flow ......... 7
- Fig. 2.2 Hypothesized relationship between tree mortality, resin flow, and beetle abundance .. 8
- Fig. 2.3 Location of study sites for measurements of growth and resin flow in mature red pine . 9
- Fig. 2.4 Representative canopy photographs used to quantify crown closure .................. 11
- Fig. 2.5 Annual radial growth of mature red pine from 1935 - 1996 ............................... 13
- Fig. 2.6 Correlations of tree age with growth and resin flow ..................................... 12
- Eq. 2.1 Resin flow in red pine as a function of tree diameter ..................................... 14
- Eq. 2.2 Resin flow in red pine as a function of tree diameter and stand basal area ........... 14
- Fig. 2.7 Average characteristics of mature red pine at 12 study sites ........................... 15
- Fig. 2.8 Average characteristics from tree-ring analyses of mature red pine at 12 study sites 16
- Fig. 2.9 Average site characteristics in 12 stands of mature red pine ........................... 17
- Fig. 2.10 Correlations among site-specific attributes of mature red pine ....................... 18
- Table 2.1 Mean attributes of 12 stands of mature red pine ........................................ 19
- Table 2.2 Correlations among site-specific attributes of mature red pine ....................... 19
- Fig. 2.11 Frequency distribution of resin flow in mature red pines vs. young red pines ....... 20
- Fig. 2.12 Average resin flow in mature red pines vs. young red pines ........................... 21
- Fig. 2.13 Relationship between site index and resin flow for red pines .......................... 21
- Fig. 2.14 Hypothesized relationship between site index and resin flow .......................... 22

CHAPTER 3. BARK BEETLE COMMUNITIES AT ITASCA STATE PARK

- Fig. 3.1 Location of pheromone trap arrays for sampling of bark beetle communities ......... 26
- Fig. 3.2 Abundance of Ips and predators in forests with and without recent windstorms ...... 27
- Table 3.1 Relative abundance of bark beetles and their predators in forests with and without windstorms ................................................................. 28
- Fig. 3.3 Seasonal patterns in trap captures of bark beetles and their predators ................... 28
- Fig. 3.4 Correlations across forest stands between the abundance of different species of Ips 29
- Fig. 3.5 Correlations across forest stands between the abundance of Ips and predators ....... 29
- Fig. 3.6 Correlations across forest stands between the abundance of different predators ..... 30
- Fig. 3.7 Captures of Ips and their predators in funnel traps baited with different pheromones 31
- Fig. 3.8 Captures of Ips pini with different enantiomeric blends of ipsdienol pheromone .... 31

CHAPTER 4. COLD TOLERANCE AND WINTER MORTALITY OF BARK BEETLES AT ITASCA STATE PARK

- Table 4.1 Lower lethal temperatures of overwintering adults of three species of Ips ........ 35
- Table 4.2 Lower lethal temperature during winter of larvae and pupae of Ips ................... 35
- Table 4.3 Overwintering microhabitats of I. pini and I. grandicollis adults ....................... 36
- Eq. 4.1 Minimum daily soil temperature as a function of air temperature and snowcover .... 36
- Fig. 4.1 Effects of air temperature and snow depth on winter soil temperatures ................. 37
- Fig. 4.2 Combinations of soil depth and air temperature that are lethal to Ips .................. 38
- Fig. 4.3 Estimated winter mortality of Ips as a function of snow depth and air temperature . 38
- Fig. 4.4 Estimated winter mortality of I. pini at Bemidji and Eau Claire from 1948-1992 .... 39
- Fig. 4.5 Minimum annual air temperatures at Bemidji and Eau Claire from 1948-1992 ....... 39
- Fig. 4.6 Dates of minimum annual air temperatures at Bemidji and Eau Claire from 1948-1992 40
- Fig. 4.7 Minimum annual soil temperatures at Bemidji and Eau Claire from 1948-1992 ....... 40
CHAPTER 5. DO BARK BEETLES KILL TREES AT ITASCA STATE PARK?

Eq. 5.1 Annual radial growth of infested trees standardized by control trees ............... 42
Fig. 5.1 Diagnostic photographs of mature red pines infested by bark beetles ............... 43
Fig. 5.2 Location of beetle-infested red pines .................................................. 44
Fig. 5.3 Photographs of crown decline in two beetle-infested trees from 1998 to 1999 .... 45
Fig. 5.4 Annual diameter growth from 1935-1996 of trees infested by beetles in 1998 .... 46
Fig. 5.5 Mean annual growth from 1935-1997 of infested red pines vs. non-infested controls. 47
Fig. 5.6 Growth rates of trees subsequently infested by Ips vs. a random sample of trees ... 47
Fig. 5.7 Hypothesized effects of bark beetles on red pine survivorship .................... 48
Table 5.1 Summary of study trees infested by bark beetles ............................... 49

CHAPTER 6. INTERACTIONS BETWEEN FIRE, BARK BEETLES, AND TREE MORTALITY

Fig. 6.1 Beetle captures in sites that were and were not burned in April 1998 ............... 53
Fig. 6.2 Resin flow in 1997 vs. 1998 for mature red pines that were and were not burned ... 54
Table 6.1 Beetle attacks in control trees vs. trees that were experimentally charred .......... 55
Fig. 6.3 Resin flow in control trees vs trees that were experimentally charred ............. 55
Fig. 6.4 Photographs of beetle attacks in charred regions of red pine trunks ............... 56
Fig. 6.5 Photographs of trees with cat-faced scars and tree that died from ignition of scar ... 57
Fig. 6.6 Schematic of the process by which fire and beetles produce cat-faced scars ..... 58
Fig. 6.7 Schematics of the feedback within a tree between damage from fire and beetles ... 59
Fig. 6.8 Schematic of the feedback within a stand between damage from fire and beetles ... 59
Fig. 6.9 Hypothetical survivorship curves for red pine with and without prescribed fires ... 60

APPENDICES

Appendix 1. Growth history from tree cores for 240 mature red pine ....................... 63
Appendix 2. Summary of growth and resin flow data for 240 mature red pine ............... 75
Appendix 4. Trap captures from sampling of bark beetle communities at Itasca ............ 83
Appendix 5. Growth history of trees subsequently infested by bark beetles ............... 103
Appendix 6. Cold tolerance of four species of bark beetles (Coleoptera: Scolytidae) in North America (manuscript in press Environmental Entomology) .................. 109
Appendix 7. Interactions between fire and bark beetles in an old growth pine forest (manuscript in press Forest Ecology & Management) ................................ 129

Volume II of the report contains three additional appendices:
A bibliography of Ips bark beetles
A bibliography of interactions between fire, trees, and insects
A bibliography of fire ecology in coniferous forests