

AN ABSTRACT OF THE THESIS OF

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Abstract approved:  Signature redacted for privacy.

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Coarse woody debris (CWD) decomposition in the Russian boreal forests of the southern taiga zone was studied at four sites located near St.-Petersburg in Northwestern Russia, Krasnoyarsk in Eastern Siberia, Irkutsk in the Baikal region, and Khabarovsk in the Russian Far East. This study was part of a broader research project assessing processes associated with accumulation, storage, and release of carbon by woody detritus in the forests of Russia.

A five-class system based on CWD visual characteristics was used to separate logs and snags into decay classes and to estimate their wood density. The largest effect on density was associated with decay classes and species. Region and position had minor effects on density. Decay-class specific density showed a gradual decrease from decay class one (least decayed) to decay class five (most decayed) regardless of species and region. Coniferous snags showed no decrease in density at least for the first two decay classes; for birch this decrease was gradual for both logs and snags. Species became more similar in density from decay class one to decay class five.

The chronosequence approach was used to study CWD decomposition by determining change in CWD mass over time. Larch (*Larix* spp.) and white pine (*Pinus siberica/koraiensis*) logs had lower decomposition rate-constants than other studied species among the regions

fluctuating between 0.015 and 0.031 year⁻¹ for larch and 0.015 and 0.019 year⁻¹ for white pine. Birch (*Betula pendula*) had the highest decomposition rate-constants among all species and regions ranging between 0.042 and 0.078 year⁻¹. No effect of temperature or precipitation on decomposition rates was observed among the studied regions, although globally there is a significant effect of temperature at least for species with non-decay resistant heartwood.

The management implications of the project results for increasing carbon storage potential of Russian forests through CWD management were examined. The current carbon store of CWD including all forest covered land and disturbed forestland was estimated to be 4.31 Pg C. Depending on species composition, this store can be either decreased to 1.56 Pg C with all tree species being replaced by birch, the fastest decomposing species, or increased to 8.11 Pg C with all species being replaced by Korean pine, the slowest decomposing species. The magnitude of these changes is substantial when compared to the potential increases in carbon sequestration of 2.02 Pg C associated with other management steps such as establishing plantations on forest and agricultural lands, reducing stand replacement fires, reducing harvest rates and increasing rotation age, increasing stand productivity via silvicultural treatments, and establishing plantations on sands, drained peat bogs, and mine tailings.

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A Chronosequence of Wood Decomposition in the Boreal Forests of Russia

by

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CONTRIBUTION OF AUTHORS

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TABLE OF CONTENTS

	<u>Page</u>
1. INTRODUCTION	1
2. BACKGROUND ON THE RESEARCH SUBJECT	5
2.1 Climate change and greenhouse gases.....	5
2.2 Importance of CWD.....	7
2.3 CWD input and decomposition.....	8
2.3.1 Factors and processes controlling CWD input.....	8
2.3.2 Factors controlling CWD decomposition.....	10
2.4 Available methods to study CWD decomposition.....	11
2.4.1 Time series	12
2.4.2 Chronosequence	12
2.4.3 Decomposition-vector.....	13
2.4.4 Input-to-biomass ratio	14
2.4.5 Dating of CWD.....	14
2.4.6 Tree Tissue Density.....	15
2.4.7 Volume correction.....	15
2.4.8 Inventory and mass or C conversion	16
2.5 Russia as a place to study CWD dynamics.....	17
2.5.1 Advantages associated with conducting the research in Russia.....	17
2.5.2 Existing information on CWD stores in Russia	17
2.5.3 Existing information on wood decomposition rates in 18	18
2.5.4 Structure of Russian forest lands.....	18
2.6 Study overview and objectives	19

TABLE OF CONTENTS (Continued)

	<u>Page</u>
3. A CHRONOSEQUENCE OF WOOD DECOMPOSITION IN THE BOREAL FORESTS OF RUSSIA	22
3.1 Abstract.....	23
3.2 Introduction	25
3.3 Study area.....	27
3.4 Methods	31
3.5 Statistical analysis.....	38
3.5.1 Decay class-specific density	38
3.5.2 Multivariate analysis of CWD visual characteristics	41
3.5.3 Decomposition rate-constants	42
3.6 Results	45
3.6.1 Decay-class specific density	45
3.6.2 Multivariate analysis of CWD visual characteristics	52
3.6.3 Decomposition rate-constants	62
3.7 Discussion.....	77
3.7.1 Decay classification	77
3.7.2 Decomposition rate-constants	83
3.8 Conclusions.....	93
3.9 References.....	96
4. MANAGEMENT IMPLICATIONS.....	102
5. SUMMARY	111
BIBLIOGRAPHY.....	114
APPENDICES	125

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
3-1. A map of Russian Federation with major cities – Regional Forest Inventory Enterprise Headquarters	28
3-2. Distribution of log density observations over the regions with potential outliers pointed out with an arrow	40
3-3. Estimates of mean specific density with error bars plotted against species by decay class.....	46
3-4. Standard deviation of mean density per decay class by species.....	48
3-5. Scree-plot of stress in relation to dimensionality	53
3-6. Overlay of variables from the “Quantitative” matrix on the “Qualitative” matrix with decay classes as the grouping variable	56
3-7. Frequency of an indicator (in percent) occurring in CWD of different decay classes by species.....	59
3-8. Results of non-metric multi-dimensional scaling analysis for 201 <i>Pinus sylvestris</i> logs and snags	61
3-9. <i>Betula pendula</i> logs collected in the St.-Petersburg region for decomposition rate calculations.....	65
3-10. <i>Picea ajanensis</i> , <i>Larix siberica</i> , and <i>Pinus siberica</i> exponential curves describing log and snag decomposition	68
3-11. The general pattern of mass percent remaining distribution over decomposition time for five species in Khabarovsk region.....	69
3-12. Comparison of regression lines of <i>Betula pendula</i> decomposition rates calculated using percent mass remaining versus percent density remaining	71

LIST OF FIGURES (Continued)

<u>Figure</u>	<u>Page</u>
3-13. Comparison of regression lines of <i>Pinus koraiensis</i> for decomposition rates calculated using percent mass remaining versus percent density remaining	71
3-14. <i>Betula costata</i> , <i>Picea ajanensis</i> , and <i>Pinus koraiensis</i> mass loss as represented by a single negative exponential curve	72
3-15. <i>Betula costata</i> , <i>Picea ajanensis</i> , and <i>Pinus koraiensis</i> fitted with separate exponential curves indicating three phases in decomposition.....	74
3-16. Decomposition rates of five species plotted against degree-days and sum of precipitation for monthly $T^{\circ}\text{C} > 5$	76
3-17. Decomposition rates obtained from different regions of the globe plotted against corresponding mean annual temperatures.....	91
3-18. Decomposition as a function of mean annual temperatures.....	92

LIST OF TABLES

<u>Table</u>	<u>Page</u>
3-1. Number of CWD pieces sampled in each region by species and position	34
3-2. Mean densities (g/cm ³) and SE's (in parenthesis) of CWD by decay class and species for major tree species of Russia	47
3-3. Comparison of the estimates of mean density among decay classes within each species	49
3-4. Tukey comparison of the estimates of mean density among species within each decay class	51
3-5. Data transformation summary sheet.....	52
3-6. Stress in relation to dimensionality (number of axes)	53
3-7. Coefficients of determination for the correlations between ordination distances and distances in the original n-dimensional space	54
3-8. Variables in the approximate sequence of their appearance and correlation coefficients between them and scores on the ordination axes.....	55
3-9. Correlation coefficients between the most important variables from "Quantitative" matrix and scores on the ordination axes.....	56
3-10. Correlations of indicator variables in ascending order to scores on the ordination axis one for five taxa well represented in the study area	58
3-11. Coefficients and SE's (in parenthesis) of the regressions of percent mass remaining over decomposition time used to estimate decomposition rate constants for species studied in four regions of Russia from west to east.....	63

LIST OF TABLES (Continued)

<u>Table</u>	<u>Page</u>
3-12. Decomposition rate comparisons (SE's for the comparison in parenthesis) based on species group runs, indicating the differences and similarities of the decomposition rates among the regions within each species	66
3-13. Decomposition time range of sampled logs and snags in different regions	67
3-14. Time periods (years) required for a given percent of mass to decompose	70
3-15. Coefficients of regression used to estimate decomposition rates in each of three phases for <i>Betula costata</i> , <i>Picea ajanensis</i> , and <i>Pinus koraiensis</i>	75
3-16. Comparison of decomposition rates determined in this study with decomposition rates obtained by other researchers in the same regions of study.....	86
4-1. Estimates of C stores, net C accumulation, and annual C flux in Russian forests	105
4-2. Management options to increase C sequestration potential of Russian forests (after Krankina et al. 1996).....	106
4-3. Carbon stores and fluxes of CWD in Russian forests.....	108

LIST OF APPENDICES

<u>Appendix</u>	<u>Page</u>
1. Climate data for the regions of study	126
2. Sampling procedure sequence and data sheet formats.....	128
3. CWD age and diameter range distributions	136
4. CWD decomposition rate constants.....	139
5. Decay class specific densities by region and species and their comparisons	143
6. List of outliers removed from the data set at each level of analysis.....	164
7. Structure of the matrices used in multivariate analysis	167

LIST OF FIGURES IN APPENDICES

<u>Figure</u>	<u>Page</u>
1-1. Comparison of trends in mean monthly temperatures and precipitation patterns among four regions of Russia	127
2-1. CWD sampling procedure and sequence	129
2-2. Diagram and a sequence of cross section processing procedure.....	129
2-3. Format one data sheet	133
2-4. Format two data sheet.....	135

LIST OF TABLES IN APPENDICES

<u>Table</u>	<u>Page</u>
3-1. Age range of CWD sampled for each decay class and species	137
3-2. Base diameter distribution among the regions and species	138
4-1. Coefficients of regressions used to estimate decomposition rate constants for studied species in four regions of Russia using percent mass remaining and an intercept of 100 percent.....	140
4-2. Coefficients of regressions used to estimate decomposition rate constants for logs and snags combined for studied species in four regions of Russia using percent mass remaining and an intercept of 100 percent.....	141
4-3. Decomposition rate comparisons (SE's in parenthesis) based on species group comparisons within each region.....	142
5-1. Mean densities (g/cm ³), SE's (in parenthesis), and number of observations (N) of <i>Abies siberica</i> CWD by decay class, position, and region.....	144
5-2. Mean densities (g/cm ³), SE's (in parenthesis), and number of observations (N) of <i>Betula costata</i> CWD by decay class, position, and region.....	144
5-3. Mean densities (g/cm ³), SE's (in parenthesis), and number of observations (N) of <i>Betula pendula</i> CWD by decay class, position, and region.....	145
5-4. Mean densities (g/cm ³), SE's (in parenthesis), and number of observations (N) of <i>Larix</i> spp. CWD by decay class, position, and region.....	146
5-5. Mean densities (g/cm ³), SE's (in parenthesis), and number of observations (N) of <i>Picea</i> spp. CWD by decay class, position, and region.....	147

LIST OF TABLES IN APPENDICES (Continued)

<u>Table</u>	<u>Page</u>
5-6. Mean densities (g/cm ³), SE's (in parenthesis), and number of observations (N) of <i>Pinus siberica/koraiensis</i> CWD by decay class, position, and region	148
5-7. Mean densities (g/cm ³), SE's (in parenthesis), and number of observations (N) of <i>Pinus sylvestris</i> CWD by decay class, position, and region.....	149
5-8. Mean densities (g/cm ³), SE's (in parenthesis), and number of observations (N) of <i>Populus tremula</i> CWD by decay class, position, and region.....	150
5-9. The comparison of <i>Abies siberica</i> log and snag estimates of mean density within decay class and region.....	150
5-10. The comparison of <i>Betula costata</i> log and snag estimates of mean density within decay class and region.....	151
5-11. The comparison of <i>Betula pendula</i> log and snag estimates of mean density within decay class and region.....	152
5-12. The comparison of <i>Larix</i> spp. log and snag estimates of mean density within decay class and region.....	153
5-13. The comparison of <i>Picea</i> spp. log and snag estimates of mean density within decay class and region.....	153
5-14. The comparison of <i>Pinus siberica/koraiensis</i> log and snag estimates of mean density within decay class and region.....	154
5-15. The comparison of <i>Pinus sylvestris</i> log and snag estimates of mean density within decay class and region.....	155
5-16. The comparison of <i>Populus tremula</i> log and snag estimates of mean density within decay class and region.....	156
5-17. Comparison of the <i>Abies siberica</i> estimates of mean density among regions for decay class and position	157

LIST OF TABLES IN APPENDICES (Continued)

<u>Table</u>	<u>Page</u>
5-18. Comparison of the <i>Betula pendula</i> estimates of mean density among regions for decay class and position	158
5-19. Comparison of the <i>Larix</i> spp. estimates of mean density among regions for decay class and position	159
5-20. Comparison of the <i>Picea</i> spp. estimates of mean density among regions for decay class and position	160
5-21. Comparison of the <i>Pinus siberica/koraiensis</i> estimates of mean density among regions for decay class and position.....	161
5-22. Comparison of the <i>Pinus sylvestris</i> estimates of mean density among regions for decay class and position	162
5-23. Comparison of the <i>Populus tremula</i> estimates of mean density among regions for decay class and position.....	163
6-1. Potential outliers removed from the decay-class specific density data set.....	165
6-2. Potential outliers removed from the NMS data set ranked by their distance to centroid	166
6-3. Potential outliers removed from the decomposition rate-constants data set.....	166
7-1. Description of the "Qualitative" matrix.....	168
7-2. Description of the "Quantitative" matrix	168

A CHRONOSEQUENCE OF WOOD DECOMPOSITION IN THE BOREAL FORESTS OF RUSSIA

CHAPTER 1

INTRODUCTION

An increase of global mean surface air temperature by about 0.5°C (IPCC 1995) and a rise of the global sea level by 10-25 centimeters during the last century (Reports to the Nation 1997) are now associated, at least in part, with the human activities of burning fossil fuels and changing land use. Although these changes in climate are often viewed as negative, not all aspects of climate change may be bad, particularly for the regions that warming may bring the benefits of increased growing season, milder winters, and narrowing diurnal temperature range (Easterling et al. 1997). However, the rate of climate change taking place, the degree it can be controlled, and the uncertainty of potential negative outcomes are most troublesome. This uncertainty, caused by our limited knowledge of the global system, means that the consequences of climate change on the environment and well being of the planet cannot be predicted.

Carbon dioxide (CO₂) is considered to be the greenhouse gas playing the most crucial role in these recent climatic changes. This is in part due to its long residence time in the atmosphere (Reports to the Nation 1997). While the role of CO₂ in regulating global climate has been fairly well understood for a century (Uppenbrink 1996), the global carbon budget is not. Manipulating the carbon cycle may be a way to mitigate climate warming. However, a “missing” carbon sink (Ciais et al. 1995) associated with partitioning of carbon fluxes between ocean and forest ecosystems

indicates we still do not fully understand all the processes regulating the current carbon cycle. Known carbon sinks in both oceans and forests are viewed by scientists as being too small to account for the entire absorption (Ciais et al. 1995). Therefore, there must be some processes of carbon sequestration that are unaccounted for at the global level. Including all the possible carbon inputs and outputs to the budget, is therefore critical for creating policies and laws that reduce atmospheric concentrations of CO₂ and reduce carbon emissions to the atmosphere (IPCC 1995, Reports to the Nation 1997).

Globally, forests play a key role in the carbon cycle with major exchanges between the atmosphere and terrestrial biosphere (Dixon et al. 1994). Whether forest ecosystems serve as a carbon sink or source is still unknown, in part due to the complexity of the ecological processes taking place in these ecosystems and our inadequate understanding of them. An improved understanding of these processes, however, is of paramount importance, given the magnitude of global forest cover, amount of carbon stored in forest ecosystems, the direct and indirect feedback control these ecosystems may have on the global climate under the influence of the climatic changes currently observed. The direct effect of forest ecosystems on climate may be associated with the cooling effect of forests on the environment as forested areas maintain cooler temperatures under the same climatic conditions than areas without forests. Also, there is a stabilizing effect between day and night temperatures with fluctuations being smaller in forest-covered areas. The indirect effect of forest ecosystems on climate may include increased net CO₂ uptake and inhibited plant respiration in response to the increases in atmospheric CO₂ (Lambers et al. 1998), as well as increased decomposition due to higher temperatures and moisture associated with an altered greenhouse effect, especially where forests are removed. The feedback of forest ecosystems to climate change may be dependent on the rate of change. If this rate is fairly low

and ecosystems have enough time to adapt, then in the long run forest ecosystems may deal with the increased CO₂ concentrations by sequestering and storing more carbon within them. If the rate of change is high, although the forest ecosystems may respond, but they may not be able to keep up with the rate of change, which may inevitably cause their destruction.

Coarse woody debris (CWD) is one carbon pool within the forest ecosystems for which little is known. While live wood inventories are common around the globe, the dead wood pool is overlooked by large-scale inventories (Kukuev et al. 1997); it thus represents a carbon pool of an unknown size and dynamics. Although rough estimates indicate that the CWD pool is relatively large (Alexeev and Birdsey 1994, Kolchugina et al. 1992, Krankina and Dixon 1994, Harmon et al. 2001), no large-scale inventories have been conducted to prove or disprove this point of view. Improved knowledge about the CWD pool, its size, and its dynamics as controlled by the ecological processes of disturbance, decomposition, and succession (Harmon et al. 1987), is crucial for understanding how this pool and forest ecosystems in general contribute to the global carbon cycle.

This study is part of a larger scientific effort assessing carbon accumulation, storage, and release by coarse woody detritus in the forests of Russia (Harmon and Krankina 1997). In addition to representing a large fraction of the global forests, Russia has large-scale live tree and partial CWD inventories (Kukuev et al. 1997) that provide a unique opportunity for conducting research on the size and dynamics of the live and dead wood carbon stores. Therefore, work in this region can help clarify the role of boreal ecosystems in the global carbon cycle. Our study examines the dynamics of CWD decomposition using a chronosequence approach (Harmon et al. 1987, Harmon and Sexton 1996), identifies the factors influencing decomposition, and calculates the CWD volume-to-mass

conversion factors required to estimate CWD carbon storage and release, which are the objectives of this study (Harmon and Krankina 1997).

To meet these objectives, I review in Chapter 2 the current knowledge about climate change and carbon balance, importance of CWD, processes controlling its accumulation and decomposition, and finally describe the methods available today to study CWD dynamics.

Chapter 3 contains the information about the study areas, statistical analysis, results of CWD chronosequences from four regions of study (Russian Northwest, Eastern Siberia, Pre-Baikal region, and Russian Far East), a discussion that includes the comparison of the results obtained in this study with other related studies, and conclusions.

Chapter 4 is devoted to discussion on management implications of the results. This chapter also examines the magnitude of the detrital C pool in comparison to other C pools within the boreal ecosystems of Russia and its potential in carbon cycle management.

Chapter 5 contains a summary of the findings of this study.

CHAPTER 2

BACKGROUND ON THE RESEARCH SUBJECT

2.1 CLIMATE CHANGE AND GREENHOUSE GASES

The increase in global atmospheric temperatures produced by the effect of increased greenhouse gas concentrations has become a major concern in the last decade of the 20th century. The first work associated with this issue, however, began in the 19th century with the Swedish scientist Svante Arrhenius who quantitatively linked CO₂ concentrations with climatic changes (Uppenbrink 1996). Arrhenius predicted a global temperature rise of 5 to 6°C for a doubling of CO₂ in the atmosphere, which is comparable to recent estimates of 1.5 to 4.5°C based on more sophisticated methods. Arrhenius estimated that it would take 3000 years for CO₂ to double as a result of fossil fuel burning by humans (Uppenbrink 1996). However, the increase in CO₂ concentration in the atmosphere is occurring at rates that are much higher than those predicted by Arrhenius. The difference is largely caused by the increased use of fossil fuels for energy production and the inability of oceans to absorb emitted CO₂ without a significant time lag. Therefore, it was emphasized by the Intergovernmental Panel on Climate Change (1995) that there is a significant short term “discernible human influence on climate.”

Although, scientific interest in the effect of climatic changes on the planet has been long-term, it has recently been brought to world's attention by the fact that the global mean surface air temperature has risen about 0.5°C (IPCC 1995) and the global sea level rose by 10-25 centimeters during the 20th century (Reports to the Nation 1997). The main cause of

this change is thought to be increased concentrations of greenhouse gases in the atmosphere. Greenhouse gases include water vapor, methane, nitrous oxide, halocarbons, tropospheric ozone, and carbon dioxide (Reports to the Nation 1997).

Of all the greenhouse gases, carbon dioxide (CO₂) has received the most attention to date in part because of its release through fossil fuel use associated with industrial revolution. It is cycled between the atmosphere and the ocean and/or the land surface by slow chemical and biological processes. Therefore, sudden addition of CO₂ to the atmosphere by burning of fossil fuels or changes in land use such as the removal of forests, for example, requires centuries for this CO₂ to be removed (Reports to the Nation 1997). The main anthropogenic sources of carbon dioxide to the atmosphere are fossil fuel burning (5.3 Pg of C per year) and changes in land use (0.4 to 2.6 Pg of C per year) (Tans et al. 1990). Roughly half of the CO₂ emitted to the atmosphere from fossil fuel burning remains in the atmosphere, while the other half is absorbed into either the oceans or the terrestrial biosphere (Ciais et al. 1995). Oceanic and terrestrial carbon sinks are viewed by chemical oceanographers and terrestrial ecologists as being too small to account for the entire absorption (Ciais et al. 1995). This raises the issue of the so-called "missing" carbon sink. For example, a net CO₂ uptake of 1.6 ± 0.07 Pg of C per year for oceans of Northern Hemisphere has been estimated with an additional 0.15 Pg of C per year for the Southern Hemisphere. This accounts for approximately 30% of the current rate of fossil fuel emissions (Tans et al. 1990). This analysis suggested that to balance the carbon budget and match the observed north-south atmospheric CO₂ gradient, there must be a net carbon sink at temperate latitudes in the Northern Hemisphere (Tans et al. 1990; Ciais et al. 1995) as large as 2.0 to 3.4 Pg of C per year. However, the mechanism of this carbon sink is largely unknown (Tans et al. 1990) in part because the

role of forest ecosystems in the global carbon cycle is still not fully understood.

2.2 IMPORTANCE OF CWD

Trees play multiple roles in forests as the primary producers, storage compartments, and support structures (Franklin et al. 1987). After a tree dies, it becomes a conspicuous component of the forest floor in most forest ecosystems (Brown et al. 1996) and continues to play numerous roles as coarse woody debris by affecting the surrounding environment and organisms (Franklin et al. 1987). Coarse woody debris reduces erosion (Swanson and Lienkaemper 1978), affects soil development (McFee and Stone 1966), functions as a habitat structure (Maser et al. 1978; Cline et al. 1980; Torres 1994), a substrate for regeneration (Harmon et al. 1986), a source (Franklin et al. 1987; Harmon et al. 1994) or sink (Franklin et al. 1987; Harmon and Chen 1991; Torres 1994) of nutrients, water, and energy. It is also a major factor controlling distribution of pathogens such as *Heterobasidion annosum*, *Armillariella mellea*, and others in forest ecosystems (Storozhenko 1994) that are suppressed by xylotrophic or dead wood destroying fungi (Storozhenko 1992).

Despite the large proportion of CWD in total forest biomass and its significant role in ecological processes, coarse woody debris was virtually ignored in older ecological studies. Recently knowledge of the ecological importance of CWD has increased dramatically (Pyle and Brown 1998) as has documentation of the amount and dynamics of dead wood (Harmon et al. 2001).

Studies conducted in forests of the Pacific Northwest (Oregon and Washington) have shown that dead boles accounted for 51 to 69% of the detrital mass with the lowest in the Washington Cascades and the highest

in the Washington Coast Range, and 6.5 to 10% of the total organic matter in the ecosystem with the lowest in the Oregon Coast Range and the highest in Washington Coast Range (Smithwick et al., unpublished). In old-growth forests of northwestern Russia dead wood comprises about 20% of the total wood biomass (Krankina and Harmon 1995). Taking into consideration that carbon accounts for 48 to 52% of live tree biomass (Harmon 1997, personal communication), global forests with their large quantity of non-photosynthetic woody mass represent a significant carbon pool relative to the size of the atmospheric pool (Gifford 1994). Given that wood decomposition is a lengthy process (Triska and Cromack 1980, Tarasov 1999), coarse woody debris in these forests is a potentially large long-term storage for carbon (Brown et al. 1996).

2.3 CWD INPUT AND DECOMPOSITION

CWD stores vary significantly in space and time and are controlled by two important processes – tree mortality and CWD decomposition. These two processes determine how much CWD is stored in an area and for how long. Mortality and decomposition depend on a number of factors that determine the overall CWD dynamics including disturbance history, structural attributes and decomposition rates of different tree species, site productivity and other factors (Krankina et al., in review).

2.3.1 Factors and processes controlling CWD input

CWD input is controlled by processes that vary temporally and spatially. Temporal variation in CWD input is associated with seasonal, annual, and successional time scales (Harmon et al. 1986). Seasonal and annual variations have been rarely studied and, depending on the

ecosystem, may include such disturbance agents as snow and ice, wind, fire, insects, floods, and droughts. Tremendous changes in the amount and type of CWD input are observed with succession (Harmon et al. 1986). While old forests contribute to CWD significantly in terms of amount and size of CWD, young forests require a long time to even reach the tree size to be allocated to CWD pool. Thus, the amount of CWD in young forests is strongly influenced by characteristics of the previous generation of trees on a given site (Harmon et al. 1986, Clark et al. 1998).

Spatial variation in CWD stores is often associated with the type of disturbance (natural vs. anthropogenic), age group of the stands, and species distribution. For example, the results based on studies of CWD stores in seven regions of Russia, indicate that the average amount of dead wood in the east is higher than that in the west with the highest stores found in naturally disturbed and young forests and the lowest occurring in young forests in the west and middle-aged forests everywhere else (Krankina et al. in review). Larch dominated middle-aged and older forests have the highest stores in most of the eastern regions, while spruce and fir dominated middle-aged and older forests have the highest stores in western regions. Birch dominated forests have the lowest stores in most of the studied regions (Krankina et al. in review). The lower stores in young forests of the West (St.-Petersburg region) are associated with clearcut harvests, which are the prevailing type of disturbance in this region, while the prevailing type of disturbance in the East (Siberia and Russian Far East) remains natural causes. The salvage of CWD in the West for firewood also contributes to lower stores in this region as compared to the East. The high stores in larch dominated forests in the East and spruce and fir dominated forest in the West are associated with the natural distribution of these species over the landscape.

2.3.2 Factors controlling CWD decomposition

Decomposition of CWD usually occurs as density loss via leaching of elements and soluble organics, microbial mineralization (i.e., respiration), and volume loss via fragmentation (Brown et al. 1996). Respiration is the primary mechanism of coarse woody debris decomposition related to density losses, and respiration rates are often used as a measure of CWD decomposition (Marra and Edmonds 1996). Fragmentation is a process associated with loss of woody material due to sloughing and breaking and is important from the viewpoint of obtaining correct estimates of CWD decomposition rates. Fragmentation is closely related to strength of the material that in turn is controlled by wood specific gravity or density (US Forest Products Laboratory 1974, Harmon 2000).

Decomposition rate as measured by mass loss (Clark 1957) is a function of debris characteristics such as physical strength, dimensions, particularly diameter (Brown et al. 1996; Tarasov 1999), external factors such as species of decay fungi (Harmon et al. 1986), moisture content, and temperature of the wood (Scheffer and Cowling, 1966), as well as the composition of air in CWD as controlled by moisture and temperature (Harmon et al. 1986). In many cases the differences in decomposition rates among the species are related to the natural resistance of different tree species heartwood to deterioration. It has been emphasized by various authors that the resistance of tree species to decay rests in the heartwood, and is affected by the deposits of toxic substances such as essential oils, tannins, and phenolic substances in dead host cells of the living tree (Scheffer and Cowling 1966; US Forest Products Laboratory 1967; Panshin and de Zoew 1970; Marra and Edmonds 1996). Other factors may include the lower moisture content of heartwood, its lower rate of diffusion, and the blocking of cell cavities by gums, resins, tyloses in the vessels, and

tylosoids in the resin canals (Panshin and de Zoew, 1970). The difference in decay resistance and thus decomposition rate of individual trees of the same species may be explained by genetic differences as well as differences in tree vigor, size (MacMillan et al. 1977; Harmon et al. 1987; Marra and Edmonds, 1996), and age (Panshin and de Zoew, 1970). Weight loss in a given period of exposure is taken as an inverse measure of decay resistance (Scheffer and Cowling, 1966). Variations in density within species do not have much effect on resistance of wood to decay, unless this higher density is correlated with greater accumulation of toxic substances (Panshin and de Zoew, 1970). Debris size is considered to have an effect on decomposition rate, because large logs were shown to have lower decomposition rates (Brown et al. 1996, Tarasov 1999) as a result of a low surface-to-volume ratio (Triska and Cromack, 1980), as well as a low ratio of sapwood to decay-resistant heartwood (Marra and Edmonds, 1996). However, small logs may dry faster, especially in hot, dry environments, and decompose slower than large logs if moisture is a limiting factor (Marra and Edmonds, 1996). Climate and microclimate have a profound effect on the decomposition process by influencing the moisture content and temperature of logs, thus affecting the microbial activity and leaching rates (Brown et al. 1996).

2.4 AVAILABLE METHODS TO STUDY CWD DECOMPOSITION

The major pathway by which C is returned to the atmosphere is through decomposition of dead boles, branches, litter, and other organic matter. Several approaches exist to estimate decomposition rates of dead boles or coarse woody debris in the form of logs and snags.

2.4.1 Time series

Time series have been used to determine decomposition rates of leaf litter (Harmon et al. 1990, Gholz et al. 2000, Hyvönen et al. 2000), fine and coarse woody debris (Harmon et al. 1995), and fine and coarse roots (Chen 1999, Gholz et al. 2000). A time series examines how a cohort of pieces progresses in decomposition through time (Harmon and Sexton 1996). This approach is a powerful tool in determining cause-effect relationships among the variables of interest including the effects of climatic and microclimatic site conditions, type and size of studied material, its position in relation to soil substrate, and other factors. It is therefore often used in scientific experiments as opposed to observational studies. It is very precise in terms of timing of events and changes occurring in the studied substances, because the studied units are monitored over the entire time of the experiment using short time-step measurements.

2.4.2 Chronosequence

The chronosequence approach has been used extensively to determine the decomposition rates of coarse woody debris (Grier 1978, Graham 1982, Harmon and Chen 1991, Busse 1994, Krankina and Harmon 1995, Chambers et al. 2000). It was also used to determine decomposition rates of coarse roots (Fahey et al. 1988, Chen 1999) and fine woody detritus (Erickson et al. 1985). A chronosequence is a specific technique of dating pieces of wood that are at different stages of decomposition by aging the logs and snags in various states of decay and examining the changes in densities, volumes, and masses of the pieces over time (Harmon and Sexton 1996). A chronosequence is therefore a substitution of space for time, where instead of monitoring changes in density, volume, and mass in a single log over a long period of time, one simultaneously samples many logs in various states of decay and records changes in their characteristics.

Although not as precise as time series measurements, chronosequences are a short-term snapshot of the decomposition process, and can give a first approximation of temporal dynamics (Harmon and Sexton 1996). The shortcomings of this approach are associated with 1) difficulties in determining the initial volume of CWD in advanced stages of decay due to significant volume loss, 2) the lack of long-term records of tree mortality (most dating techniques are associated with some error), and 3) the fact that one can only date those CWD pieces that are found. This means that some of the CWD can be completely decomposed by the time of sampling or buried in the soil or peat. Overlooking the former form of CWD can overestimate decomposition rates. Overlooking the latter not only can underestimate the decomposition rates but in relation to buried pieces, can underestimate CWD stores.

Chronosequencing of different aged stands can also be used to indirectly estimate the decomposition rates of woody detritus (Gore and William 1986, Spies et al. 1988, Wirth et al. 2000) with the assumption that each stand-replacing catastrophic disturbance left a similar amount of material. Taking into account the temporal and spatial variation associated with different types of disturbance, this assumption often is not justified (Harmon and Sexton 1996).

2.4.3 Decomposition-vector

The decomposition-vector method was first used by Harmon et al. (2000) to estimate rates of biomass, volume, and density loss for the CWD pieces with a 3-year resampling interval. This method represents a hybrid between the chronosequence and time-series approach in that the primary estimates of CWD dynamics (mass loss over time) are done in accordance with the chronosequence method, while future monitoring of these dynamics is done according to time-series (Harmon and Sexton 1996). The

method takes advantage of examining the extended decomposition process in a relatively short period of time, because the monitoring starts on pieces at various stages of decay. This allows one to represent the decomposition process in a series of short steps each with its own decomposition rate. The disadvantages of this approach are similar to those of chronosequencing and are associated with errors of initial volume adjustments of severely decomposed CWD and decomposition time estimations.

2.4.4 Input-to-biomass ratio

The input-to-biomass ratio approach involves estimation of CWD decomposition rates from the ratio of CWD inputs due to mortality to CWD biomass in the stand. It gives reliable results in old forests with long-term mortality records. It usually results in estimates of decomposition rates higher than those measured by the chronosequence (Sollins 1982, Harmon and Chen 1991). Limitations associated with the input-to-biomass approach have to do with the assumption of steady-state CWD biomass, which is often not justified due to the high variability of both inputs and stores of woody detritus (Harmon et al. 2001).

2.4.5 Dating of CWD

Dating of CWD pieces is most widely used in the chronosequences. It is done to determine the times various pieces have been decomposing. The logs and snags in the chronosequence can be dated using permanent plot records, history of catastrophic disturbances, fire scars, or scars formed on live trees by fallen trees, ages of seedlings growing on logs, ages of stands, or any other evidence that can possibly give a reliable CWD decomposition time. Dendrochronology or cross-dating is another way to

date CWD. This technique involves matching the growth ring sequence of snags and logs to the growth ring sequence of live trees in the stand to determine the time when tree death occurred (Ghent 1952, Van Densen et al. 1991, Veblen et al. 1991, Pedersen 1992). Dating techniques, other than permanent plot records, all are associated with significant error, the magnitude of which is positively correlated with the decomposition time.

2.4.6 Tree Tissue Density

Changes in wood and bark densities have been used by various scientists to study decay (Triska and Cromack 1980, Harmon and Chen 1991, Brown et al. 1996, Tarasov 1999, Shorohova and Shorohov 1999). Density is often expressed as a ratio of dry mass to “green” volume. Most woods at usual moisture contents have densities less than 1g/cm^3 (Panshin and de Zoew 1970). As decay advances, there is a progressive decrease in wood density (Triska and Cromack 1980, Harmon et al. 1987, Hale and Pastor 1998, Shorohova and Shorohov 1999), because of destruction of the wood by deteriorating organisms and leaching. This process is usually described by a single exponential equation (Olson 1963):

$$\text{density}_t = \text{density}_0[\exp(-kt)],$$

where t is the decomposition time, density_t is the residual density, density_0 is the initial density, and k is the decomposition rate.

2.4.7 Volume correction

Major underestimates of decay losses and nutrient flux can be made if decomposition rate calculations are based strictly on density loss over time while ignoring the fragmentation losses (Krankina and Harmon 1995).

About 30% of the mass of CWD logs is lost via fragmentation (Graham and Cromack 1982, Harmon and Chen 1991), thus fragmentation losses from the bole should be included in the decomposition rate estimates (Harmon and Sexton 1996). Not all volume loss, however, is due to transfer of coarse material to the fine fraction. Some is due to complete respiration. For example, it is not unusual to find the upper portion of dead trees missing (Harmon et al. 1987). The other source of fragmentation is associated with a transfer of CWD from one form to another (e.g., snags becoming logs).

2.4.8 Inventory and mass or C conversion

The mass, nutrient, and C stores in CWD can be estimated in fixed area plots (Harmon and Sexton 1996). The inventory of CWD is often done in plots (Harmon et al. 1986, Harmon and Sexton 1996) by recording the dimensions of a piece (diameters on both ends and the middle, and the length) as well as its species and stage of decomposition (decay class). Other methods to estimate dead wood stores are known such as line transects or line intercepts (for log inventory) and variable radius plots for suspended wood inventory (Harmon and Sexton 1996) can be used.

Regardless of the method, the plot area or transect length is recorded to calculate the CWD distribution per unit area. Once the CWD volume by species and decay class is obtained, the mass is calculated as a product of volume and decay-class specific density by species (Harmon and Sexton 1996). The carbon-to-mass ratio of CWD is roughly 0.5 (Sollins et al. 1987) for all decay classes.

2.5 RUSSIA AS A PLACE TO STUDY CWD DYNAMICS

2.5.1 Advantages associated with conducting the research in Russia

At the global scale Russia is an important region to improve our understanding of CWD. First of all, Russian forests comprise about 20% of the global forests and 50% of the global boreal forests (Krankina and Harmon 1995). Thus, learning about the processes that take place in Russian forests would contribute significantly to understanding the role of forest ecosystems in global CWD and C dynamics. Second, Russia has a live and dead wood inventory system that would allow one to determine how this portion of the world contributes to global carbon fluxes associated with CWD dynamics (Kukuev et al. 1997). Third, Russia, having been behind closed doors for an extended period represents a “black hole” in global ecological knowledge. Only in the last decades has ecological information started to surface from this part of the world (Kobak 1988, Kolchugina et al. 1992, Basilevich 1993, Isaev et al. 1993, Krankina and Dixon 1994, Storozhenko 1994, Filimonov et al. 1995, Krankina and Harmon 1995, Kukuev et al. 1997, Alexeyev and Birdsey 1998, Tarasov 1999, Shorohova and Shorohov 1999, Shorohova 2000, Harmon et al. 2000, Krankina et al. in press, Krankina et al. in review).

2.5.2 Existing information on CWD stores in Russia

In recent years significant information about CWD stores in Russia has appeared in the literature. Most of it, however, is related to the Northwestern part of Russia. Average CWD stores in the Russian Northwest range from 1.7-2.4 Mg/ha in young forest stands, to 5.9-7.0 Mg/ha in middle-aged, and to 9.3-11.1 Mg/ha in mature and older stands (Krankina et al. in press). Other sources obtained by modeling of tree mortality and decomposition rates indicate stores of 14-42 Mg/ha in mature

forests for the St.-Petersburg region (Tarasov 1999). A wide range of CWD stores, fluctuating between 6.6 and 102 Mg/ha, was observed among the sites for old-growth spruce forests of this region (Shorohova and Shorohov 1999). Smaller differences were reported to occur among large regions. Average CWD stores in the East Siberian and Far Eastern regions fluctuate between 11.0 and 14.3 Mg/ha (Krankina et al. in review). Other studies have estimated widely divergent average CWD stores of a 7.4 Mg/ha for the European and 15 Mg/ha for the Asian parts of Russia (Shvidenko and Nilsson 2000), and of 34-40 Mg/ha for the entire country (Moiseev et al. 2000).

2.5.3 Existing information on wood decomposition rates in Russia

Existing information about wood decomposition rates is limited to a few species and a few studies that were mostly conducted in the Russian Northwest. Birch, spruce, and pine were reported to decompose in the St.-Petersburg region by various authors at rates of 5.8% (birch), and 3.1% (spruce) year⁻¹ (Shorohova 2000); 4.6% (birch), 3.3% (spruce), and 3.5% (pine) year⁻¹ (Harmon et al. 2000); 2.6 to 5.1% (birch), 1.9 to 3.3% (spruce), and 1.4 to 2.3% (pine) year⁻¹ (Tarasov 1999); and 4.5% (birch), 3.4% (spruce), and 3.3% (pine) year⁻¹ (Krankina and Harmon 1995). Pine was also reported to decompose at a rate of 3.4% year⁻¹ in Western Siberia (Wirth et al. 2000).

2.5.4 Structure of Russian forest lands

Although, the structural attributes of Russian forest lands was not directly used in this project, it can present great advantages in calculating CWD and C stores. When decay-class specific densities determined in this study are combined with live and dead wood forest inventories, C

stores can be calculated not only for the areas that undergone live and CWD inventories, but they also can be estimated using live to dead wood ratios for the areas lacking CWD inventory. In addition, C turnover time based on C stores coupled with the decomposition rates estimated in this study can be calculated.

The entire territory of Russia can be divided into four major geographic regions: Europe-Urals, Western Siberia, Eastern Siberia, and Russian Far East. Each of the regions is subdivided into regional infrastructure units (oblast', krai, etc.) which in turn are broken into Forest Management Enterprises (FME's) or as they are called in Russia "leskhoz." FME's are primary forest management units in Russia (similar to National Forests in the U. S.) ranging in size from 20 thousand to several million ha. Every FME is represented by the numerous ranger districts or "lesnichestvo." The ranger districts in turn are broken down into stands, with the stand as a smallest unit of management. Forestlands are inventoried and a new long-term forest management plan is developed for each FME every 10-20 years. This work is the responsibility of the Russian Federal Forest Service Department of Forest Inventory and its regional offices known as Forest Inventory Enterprises (FIE's). The 87.5% (Krankina et al. 1996) of the forests that are under state forest management have been inventoried with up to 300 different characteristics collected for each stand (Kukuev et al. 1997).

2.6 STUDY OVERVIEW AND OBJECTIVES

This study is part of a broader research project that is examining carbon accumulation, storage, and release by woody detritus in the forests of Russia (Harmon and Krankina 1997). The broader research project developed a system of expansion factors to estimate woody detritus

biomass from inventory data. For this purpose the inventory data were divided into two groups. One contains inventory data including stand-level visual estimates of CWD stores. For inventory data containing these visual CWD store estimates, correction factors were calculated based on the ratio of measured volume to visually estimated volume (Krankina et al. in review). The second group lacks these visual CWD store estimates. In this case, expansion factors, based on the ratio of CWD volume to wood volume of live trees, are used (Krankina et al. in review). For both groups correction factors were calculated based on forest stand parameters such as stand age group and dominant species (Harmon and Krankina 1997). This broader research relies heavily on the volume to carbon conversion factors and wood detritus decomposition rates that are a major part of the current study.

The overall goal of this study was to understand the wood decomposition dynamics of different species in the southern taiga zone of the boreal forests of Russia and determine the differences and similarities of these dynamics among the species and regions sampled. We wanted to see if the differences in site climatic conditions such as temperature and precipitation influence the decomposition processes at these sites or if the primary control was species. Also, in this study we developed a decay class system for major tree species of the boreal forest of Russia and identify the characteristics that can simplify the CWD inventory in the field.

The specific objectives of the study were:

1. To develop a five-decay class system for the major tree species of Russia for a CWD inventory and determine the decay-class specific density for the conversion of CWD volume into mass and C stores in seven regions of Russia.

2. To determine woody detritus decomposition rates of major tree species in four geographic regions of Russia.
3. To examine the differences in decomposition rates associated with tree species, CWD position, and region of study.
4. To examine the impact of climate characteristics such as mean annual temperatures and annual precipitation, or degree-days and sum of precipitation over the days with $T^{\circ}\text{C} > 5$ on decomposition rates.
5. To assess the management implications of these results for increasing carbon storage potential of Russian forests.

CHAPTER 3

A CHRONOSEQUENCE OF WOOD DECOMPOSITION IN THE BOREAL FORESTS OF RUSSIA

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3.1 ABSTRACT

Coarse woody debris (CWD) comprised of logs and snags of at least 10 cm in lower-end diameter and at least 1 m in length was studied at six sites located in the boreal forests of Russia in the southern taiga zone. Logs and snags of major forest-forming species including *Abies siberica* Ledeb., *Betula pendula* Roth., *Betula costata* Trautv., *Larix siberica* Ledeb., *Larix dahurica* Turcz., *Picea abies* (L.) Karst., *Picea obovata* Ldb., *Picea ajanensis* Fisch., *Pinus koraiensis* Sieb. et Zucc., *Pinus siberica* Ledeb., *Pinus sylvestris* L., and *Populus tremula* L. were measured and sampled to determine decay-class specific density and decomposition rates by species, position, and region. A total of 970 logs and snags were sampled and used to calculate decay-class specific density, and 693 of them were used in the chronosequence to determine decomposition rates. For five decay classes that included logs and snags of various stages of decomposition from least decayed (class one) to most decayed (class five), the mean specific densities ranged between 0.285 and 0.516, 0.320 and 0.424, 0.194 and 0.368, 0.120 and 0.204, and 0.084 and 0.173, respectively. No significant differences were found in mean densities for the same species among the regions or between logs and snags of the same decay class. However, some differences between the mean specific densities of logs and snags in decay classes two and three were detected for coniferous species such as *Larix* spp., *Picea* spp., *Pinus siberica*, and *Pinus koraiensis*. No differences in mean density were found between logs and snags of *Betula pendula* regardless of decay class. An ordination of the presence/absence of visual characteristics such as bark on bole, branches, bark on branches, sapwood sloughing, sapwood friable, heartwood friable, log collapsing, etc. indicated that bark on bole may be a single most important characteristic separating *Betula pendula* from the conifers. Among the conifers, sapwood friability and sloughing in decay class two

and bark on bole from decay class one to decay class four were the main differences between *Pinus siberica/koraiensis* and other species. Annual decomposition rates varied among the species, positions, and regions, and fluctuated for logs between 4.2% and 7.8% for *Betula pendula*, 2.6% and 4.9% for *Picea* spp., 2.7% and 4.4% for *Pinus sylvestris*, 1.5% and 3.1% for *Larix* spp., and 1.5% and 1.9% for *Pinus koraiensis* and *Pinus siberica*, respectively. Most of the variance in percent mass remaining was explained by position. However, due to difficulties associated with locating snags in advanced stages of decay, many of the snag decomposition rates were not significantly different from zero. The calculated CWD half-life, time to 95% and time to 99% mass loss, indicated that *Betula pendula* is the fastest decomposing species and *Pinus koraiensis* is the slowest decomposing species among those studied.

The influence of temperature and precipitation on decomposition rates of the studied species did not show any strong pattern of rate change with increase of mean annual temperature or precipitation. When degree-days and sum of precipitation with $T^{\circ}\text{C} > 5$ was used, the *Betula pendula* log decomposition rate had a positive correlation with these climatic factors, while *Pinus siberica/koraiensis* had a negative correlation with the sum of precipitation. Other species did not show any relation of decomposition rates to these climatic factors, suggesting that the climatic range over which the sampling for decomposition rates occurred was too narrow to show any temperature or precipitation effect. In the global context, our data were consistent with other studies indicating a positive correlation between decomposition rates of decay-susceptible species and mean annual temperatures, with the largest effects of temperatures appearing in the tropics and subtropics. The effect of temperature on the decomposition rate of decay-resistant species was minor.

3.2 INTRODUCTION

An increase of global mean surface air temperature by about 0.5°C (IPCC 1995) and a rise of the global sea level by 10-25 centimeters during the last century (Reports to the Nation 1997) are now associated, at least in part, with the human activities of burning fossil fuels and changing land use. Although these changes in climate are often viewed as negative, not all aspects of climate change may be bad, particularly for the regions that warming may bring the benefits of increased growing season, milder winters, and narrowing diurnal temperature range (Easterling et al. 1997). However, the rate of climate change taking place, the degree it can be controlled, and the uncertainty of potential negative outcomes are most troublesome. This uncertainty, caused by our limited knowledge of the global system, means that the consequences of climate change on the environment and well being of the planet cannot be predicted.

Carbon dioxide (CO₂) is considered to be the greenhouse gas playing the most crucial role in these recent climatic changes. This is in part due to its long residence time in the atmosphere (Reports to the Nation 1997). While the role of CO₂ in regulating global climate has been fairly well understood for a century (Uppenbrink 1996), the global carbon budget is not. Manipulating the carbon cycle may be a way to mitigate climate warming. However, a “missing” carbon sink (Ciais et al. 1995) associated with partitioning of carbon fluxes between ocean and forest ecosystems indicates we still do not fully understand all the processes regulating the current carbon cycle. Known carbon sinks in both oceans and forests are viewed by scientists as being too small to account for the entire absorption (Ciais et al. 1995). Therefore, there must be some processes of carbon sequestration that are unaccounted for at the global level. Including all the possible carbon inputs and outputs to the budget, is therefore critical for creating policies and laws that reduce atmospheric concentrations of CO₂

and reduce carbon emissions to the atmosphere (IPCC 1995, Reports to the Nation 1997).

Globally, forests play a key role in the carbon cycle with major exchanges between the atmosphere and terrestrial biosphere (Dixon et al. 1994). Whether forest ecosystems serve as a carbon sink or source is still unknown, in part due to the complexity of the ecological processes taking place in these ecosystems and our inadequate understanding of them. An improved understanding of these processes, however, is of paramount importance, given the magnitude of global forest cover, amount of carbon stored in forest ecosystems, the direct and indirect feedback control these ecosystems may have on the global climate under the influence of the climatic changes currently observed. The direct effect of forest ecosystems on climate may be associated with the cooling effect of forests on the environment as forested areas maintain cooler temperatures under the same climatic conditions than areas without forests. Also, there is a stabilizing effect between day and night temperatures with fluctuations being smaller in forest-covered areas. The indirect effect of forest ecosystems on climate may include increased net CO₂ uptake and inhibited plant respiration in response to the increases in atmospheric CO₂ (Lambers et al. 1998), as well as increased decomposition due to higher temperatures and moisture associated with an altered greenhouse effect, especially where forests are removed. The feedback of forest ecosystems to climate change may be dependent on the rate of change. If this rate is fairly low and ecosystems have enough time to adapt, then in the long run forest ecosystems may deal with the increased CO₂ concentrations by sequestering and storing more carbon within them. If the rate of change is high, the forest ecosystems may respond, but they may not be able to keep up with the rate of change, which may inevitably cause their destruction.

Coarse woody debris (CWD) is one carbon pool within the forest ecosystems for which little is known. While live wood inventories are

common around the globe, the dead wood pool is overlooked by large-scale inventories (Kukuev et al. 1997); it thus represents a carbon pool of an unknown size and dynamics. Although rough estimates indicate that the CWD pool is relatively large (Alexeev and Birdsey 1994, Kolchugina et al. 1992, Krankina and Dixon 1994, Harmon et al. 2001), no large-scale inventories have been conducted to prove or disprove this point of view. Improved knowledge about the CWD pool, its size, and its dynamics as controlled by the ecological processes of disturbance, decomposition, and succession (Harmon et al. 1987), is crucial for understanding how this pool and forest ecosystems in general contribute to the global carbon cycle.

This study is part of a larger scientific effort assessing carbon accumulation, storage, and release by coarse woody detritus in the forests of Russia (Harmon and Krankina 1997). In addition to representing a large fraction of the global forests, Russia has large-scale live tree and partial CWD inventories (Kukuev et al. 1997) that provide a unique opportunity for conducting research on the size and dynamics of the live and dead wood carbon stores. Therefore, work in this region can help clarify the role of boreal ecosystems in the global carbon cycle. Our study examines the dynamics of CWD decomposition using a chronosequence approach (Harmon et al. 1987, Harmon and Sexton 1996), identifies the factors influencing decomposition, and calculates the CWD volume-to-mass conversion factors required to estimate CWD carbon storage and release.

3.3 STUDY AREA

The study area includes six locations in different parts of Russian boreal forest (Figure 3-1). Data collection occurred during 1993 and the period from 1996 to 1999. Data collection for decay-specific density calculations took place in all six regions, while sampling for the

decomposition rate calculations took place in the St.-Petersburg, Krasnoyarsk, Irkutsk, and Khabarovsk regions.

Figure 3-1. A map of Russian Federation with major cities – Regional Forest Inventory Enterprise Headquarters



The data from the first site were collected during the field seasons of 1993 and 1996 in the St.-Petersburg region of Northwestern Russia located at about 59°N and between 31 and 32°E (Harmon et al. 2000). The climate in this FME is cool maritime with cool wet summers and long cold winters (Krankina et al. 1999). The mean annual temperature of July is 16.5°C, while the mean temperature of January is -8.5°C. The mean annual precipitation is 708 mm (Appendix 1).

Data from the second site were collected during the 1997 field season in the Chunoyarskii FME (leskhoz) of the Krasnoyarsk Regional

Forest Management Department. It is located in the northeast area of Krasnoyarskii Krai in the territory of Boguchanskii county. This FME includes three ranger districts (lesnichestvo): Takuchetskoe (532.3 thousand ha), Chunoyarskoe (193.3 thousand ha), and Khozhinskoye (184.4 thousand ha).

The total area of the FME is 910 thousand ha, and is located along the banks of the Chuna river. It belongs to the Angara province of the southern taiga and is dominated by larch-pine (*Larix siberica* – *Pinus sylvestris*) forests. The climate is moderately cold and continental. The vegetation period lasts 126 days with a frost-free period of 110 days. The mean annual temperature of July is 16°C, while the mean temperature of January is –25°C, and the overall mean annual temperature is –3.2°C. The mean annual precipitation is 361 mm (Appendix 1).

Data from the third site were collected during the 1998 field season in the Bayandaiskii and Ol'khonskii FME's of the Irkutsk Regional Forest Management Department. The Ol'khonskii FME is located along northwest bank of Lake Baikal in the territory of Ol'khonskii county, while the Bayandaiskii FME is located approximately 120 km from Lake Baikal along the major highway connecting the city of Irkutsk with the northwest bank of the lake. Sampling for density and decomposition rates was done in the Bayandaevskoe ranger district of Bayandaiskii FME and Ol'khonskoe ranger district of Ol'khonskii FME. The districts are adjacent and located close to the meteorological station at Yelantsy. The mean temperature of July is 17°C and mean temperature of January is -20°C. The overall mean annual temperature is –0.6°C and the mean annual precipitation is 216 mm (Appendix 1). The site is located in the area of strictly continental climate with permafrost. Forests in the south are primarily comprised of Scots pine (*Pinus sylvestris*). In mountainous regions Siberian larch (*Larix siberica*), Siberian white pine (*Pinus siberica*), and spruce (*Picea obovata*) are

common, and are associated with small amounts of Siberian fir (*Abies siberica*).

The fourth site in this study was sampled during the 1999 field season and is located in the Khorskii FME of the Khabarovsk Regional Forest Management Department. This FME includes six ranger districts (lesnichestvo), only three of which were used for data collection: Lazovskoe (241.6 thousand ha), Katenskoe (313.7 thousand ha), and Kafenskoe (245.8 thousand ha). The total area of this FME is 1029 thousand ha. The territory of this FME can be divided into eastern mountainous and western lowland parts. The mountainous part includes the Sikhote-Alin Range and surrounding areas and occupies 90 percent of the FME's territory. The lowland portion of the FME is in the southwestern part of the Amur Lowland. The Katenskoe and Kafenskoe ranger districts' elevation fluctuates between 600 and 800 meters above sea level, while for the Lazovskoe district ranges between 400 m and 600 m. Due to the wide range of the elevations, meteorological data from two stations, Bichevaya and Cherinai, were included with elevations of 102.9 m and 737 m above sea level, respectively. Due to the strong influence of the Japan Sea, this area has conditions favorable for plant growth with an elongated vegetation period and increased summer temperatures. Continental climate is prevalent during dry, cold winter with low snow levels. This climate promotes growth of a wide range of plant species that includes Korean white pine (*Pinus koraiensis*), spruce (*Picea obovata*), true fir (*Abies siberica*), ash (*Fraxinus mandschurica* Rupr.), walnut (*Juglans mandschurica* Maxim.), bathwood (*Tilia* spp.), yellow birch (*Betula costata*), Mongolian oak (*Quercus mongolica*), maples (*Acer* spp.), hazelnut (*Corylus heterophylla* Fisch. ex Bess.), euonymus (*Euonymus* spp.), philadelphus (*Philadelphus* spp.), eleuthero (*Eleutherococcus senticosus* (Rupr. et Maxim.) Maxim.), limonnik (*Schizandra chinensis* (Turcz.) Baill.), aktinidia (*Actinidia kolomikta* Maxim.), and Amur grape (*Vitis amurensis* Rupr.) (Usenko 1969). The vegetation

period lasts 174 days in lowlands and 158 days in mountainous areas. The mean temperature of July is 17°C, while mean temperature of January is – 24°C, with an overall annual mean of –1.9°C. The mean annual precipitation is 909 mm (Appendix 1). Seventy four to eighty two percent of the precipitation occurs during the warm part of the year with the mountainous parts getting considerably more precipitation than the lowlands.

3.4 METHODS

This project had two interrelated parts: 1) calculation of decay-class specific density and 2) estimation of decomposition rates for the common species in four regions of Russia. The choice of the FME for sampling depended largely on each Forest Inventory Enterprise's plans for inventory. This allowed us to work jointly with inventory crews reducing transportation, rent, fuel, and lodging costs.

Three different parties were responsible for the data collection. In the St.-Petersburg region the 1993 and the 1996 part of data collection for the decay-class specific density and decomposition rate was accomplished by Harmon and Krankina (Krankina and Harmon 1995). During the same 1996 field season, the data collection for the decay-class specific density calculations was done in St.-Petersburg, Novosibirsk, Krasnoyarsk, and Irkutsk regions by the students of the St.-Petersburg Forest Technical Academy. The 1997 through 1999 data collection for the decay-class specific density calculations was done by the employees of Regional Forest Inventory Enterprises of the Russian Forest Service in Moscow (1999), Novosibirsk, Krasnoyarsk (1999), Irkutsk (1997), and Khabarovsk (1997, 1998). The data collection for the decay-class specific density and decomposition rate calculations during those three field seasons was

accomplished by Krankina, Yatskov M. and Yatskov A. in Krasnoyarsk (1997), Irkutsk (1998), and Khabarovsk (1999).

The most representative species (three coniferous and one hardwood) were determined in each region using the FME inventory records. Then, the average age and average diameter were calculated for each species and only snags and logs exceeding the live age and size average for FME were sampled. Sampling the woody debris of the representative age classes and sizes was considered to be crucial because of the difference in decomposition rates of young and old trees (Clark 1957). In addition, logs and snags with a length to mean diameter ratio of 10 and higher were sampled to reduce effects of elevated decay at ends of pieces (Harmon and Sexton 1996).

A chronosequence approach was used as the major technique to estimate decomposition dynamics of the sampled species in the four different regions. A chronosequence, being a substitution of space for time, is created by aging (estimating decomposition time) of logs and snags in various states of decay and examining the changes in density of pieces over time (Harmon and Sexton 1996). Although not as precise as time series measurements, a chronosequence is a short-term snapshot of the decomposition process, and can give a valid first approximation of temporal dynamics.

Stands damaged by major disturbances and timing of these disturbances were determined in each region in Russia. This information was gathered from the FME records and history of the local forest industry. The disturbances examined included fires, windbreak, windthrow, beetle kill, Asian gypsy moth kill, road construction, and various types of cuttings (clearcut, partial cut, selective cut). A preference in sampling location was given to naturally disturbed stands, while stands that had experienced anthropogenic disturbances (road construction, and various types of cuts) were considered last for sampling. An exception was for trees cut in the

past for construction of growth and yield tables. In most cases, these logs decomposed in common microclimatic conditions (under the canopy of trees) and it was easy to determine the precise date of their harvest.

Over the course of five years (1993, and 1996-1999) a total of 970 logs and snags were sampled for the purpose of decay-class specific density calculations in 6 regions of Russia including from west to east, St.-Petersburg, Central (Moscow), Novosibirsk, Krasnoyarsk, Irkutsk, and Khabarovsk (Table 3-1). We were able to determine decomposition time for 693 logs and snags. These were sampled in four regions (St.-Petersburg, Krasnoyarsk, Irkutsk, and Khabarovsk).

Once CWD pieces were selected for sampling, they were assigned to one of five decay classes based on visual characteristics that included presence of leaves, twigs, branches, bark cover on branches and bole, sloughing of wood, collapsing and spreading of log (indicating the transition from round to elliptic form), friability of wood, and mobility of branch stubs (Triska and Cromack, 1980; Graham and Cromack, 1982; Sollins 1982; Harmon and Sexton, 1996). This approach was taken to be consistent with the forest inventory crew, who based their decision about log and snag decay class only on visual characteristics.

Before density sampling took place, log dimensions including length, base and top diameters, and current DBH were recorded. Visual characteristics that are used to distinguish between the decay classes were also recorded at that time (Appendix 2) as well as the biological indicators such as moss cover, presence of fungal fruiting bodies, presence of insect galleries and others.

In-field dating of logs was done using the inventory records of catastrophic events, the record of permanent plots used for growth and yield table construction, the information from the local population about timing of natural or anthropogenic disturbances, the age of young stands regenerating after a disturbance, the age of a tree growing on a log, the age

Table 3-1. Number of CWD pieces sampled in each region by species and position

Region	Species	Position	Decay Class count	Decomposition rate count
Irkutsk	<i>Betula pendula</i>	Log/Snag	41/17	41/17
	<i>Larix siberica</i>	Log/Snag	45/28	42/28
	<i>Picea obovata</i>	Log	22	--
	<i>Pinus siberica</i>	Log/Snag	40/17	33/17
	<i>Pinus sylvestris</i>	Log/Snag	54/21	35/19
	<i>Betula costata</i>	Log/Snag	23/7	23/7
Khabarovsk	<i>Betula pendula</i>	Log/Snag	21/7	20/7
	<i>Larix dahurica</i>	Log/Snag	53/10	26/10
	<i>Picea ajanensis</i>	Log/Snag	53/14	39/14
	<i>Pinus koraiensis</i>	Log/Snag	36/13	35/13
	<i>Populus tremula</i>	Log/Snag	5/1	--
	<i>Quercus mongolica</i>	Log/Snag	3/3	--
Krasnoyarsk	<i>Abies siberica</i>	Log/Snag	17/6	--
	<i>Betula pendula</i>	Log/Snag	28/13	28/13
	<i>Larix siberica</i>	Log/Snag	32/8	30/8
	<i>Picea obovata</i>	Log/Snag	33/8	31/8
	<i>Pinus sylvestris</i>	Log/Snag	45/10	31/8
	<i>Populus tremula</i>	Log	20	--
	<i>Quercus robur</i>	Log	1	--
N. Novgorod	<i>Betula pendula</i>	Log	15	2
Novosibirsk	<i>Abies siberica</i>	Log/Snag	14/6	--
	<i>Betula pendula</i>	Log/Snag	31/4	2/--
	<i>Pinus sylvestris</i>	Log/Snag	17/3	--
St.-Petersburg	<i>Betula pendula</i>	Log/Snag	18/10	11/7
	<i>Picea abies</i>	Log/Snag	21/7	20/7
	<i>Pinus sylvestris</i>	Log/Snag	43/14	42/14
	<i>Populus tremula</i>	Log/Snag	11/1	4/1
Total			970	693

of a fire scar on living tree, and the age of a scar left by a fallen tree. While the sample collection procedure for decay class density and decomposition rate estimation was the same, the decomposition rate calculations, required decomposition time and additional information on mass loss via fragmentation (Harmon et al. 2000).

Four cross sections (samples) were cut with a chainsaw from each log or snag that was sampled and served as a primary sampling unit (Appendix 2). The four cuts were located equidistant along the bole. If the sampled log was short, which happened often in more advanced decay classes, only two or three samples were taken. The diameters of all cross sections and the distances of each from the base were recorded within 1 cm. The tree lengths and distances of cross sections from the tree base were recorded within 10 cm. All cross sections extracted from the sampled logs were processed (Appendix 2) at the site or shortly after returning to base camp to insure that temperature and moisture did not promote further deterioration. For the purpose of this study, bark and wood tissues were sampled separately as they have very different decomposition rates. Outermost cross-section diameter, bark and wood longitudinal thickness, wood radial depth of rot, and bark radial thickness were measured on each cross-section. Bark was separated from wood and the weight of each was determined. Bark and wood subsamples of approximately 50 g were taken, weighed, placed into the marked cloth bags indicating the region, species, cross-section number, and type of tissue, and placed in an attic to air dry. All weights in Russia were measured on a portable electronic scale with a precision of 0.1 g (0.01g for weights measured in the U.S.). All the diameters, bark circumferential length, and average depth of rot were measured with a diameter tape and recorded in centimeters with a precision of 0.1 cm. The radial and longitudinal thickness were measured with a ruler and recorded in millimeters as the average of at least four measurements with a precision of 1 mm.

Subsample (wood and bark) dry weights were determined in the lab after oven drying at 55°C until a constant subsample weight was reached. To ease the weighing process, the subsamples were removed from the cloth bags upon arrival from Russia and placed into pre-weighed paper bags with a bar-code sticker.

The calculations of bark and wood sample density involved two steps. The first step included the calculations of bark and wood sample dry weights as:

$$DW_s = WW_s * \frac{DW_{ss}}{WW_{ss}}, \text{ where}$$

DW_s – sample dry weight, WW_s – sample wet weight, DW_{ss} – subsample dry weight, and WW_{ss} – subsample wet weight.

The second step included the calculations of the sample densities as:

$$D_s = \frac{DW_s}{V_s}, \text{ where}$$

D_s – sample density, DW_s – sample dry weight, and V_s – sample volume.

For the purpose of obtaining the current density of each CWD piece we first calculated the current volume as a sum of the volumes of sections that were determined based on base, top, and cross-section outside or inside bark diameters and distances between cross-sections. Then we calculated total mass as a sum of the mass of each section obtained as a product of section volume and cross-section density. A mean density of

log/snag was obtained by dividing the current total mass by total current volume.

These mean densities were also used to calculate decomposition rates, however, there is a problem with fragmentation losses. To account for wood fragmentation losses over the course of decomposition, an attempt was made to reconstruct the original tree volume from DBH either measured directly or determined by reconstruction in the field. Several methods were used for this purpose. For missing bark, DBH without bark and missing bark thickness were measured. For DBH without bark its thickness was estimated from measurements in other parts of the bole. For DBH of boles with missing bark and some wood fragmentation, DBH without bark, missing bark thickness, and radial thickness of missing wood were determined (Harmon and Sexton, 1996). If the DBH location on a log or snag was severely damaged, the measurements of base diameter from a stump, base, or outside bark diameter at a distance from tree base were used to determine the original DBH from taper equations. Once, an original DBH was obtained from one of mentioned methods, the original volume was determined from growth and yield tables (Tret'yakov 1952, USSR Federal Forestry Committee 1961, Koryakin 1990) using reconstructed DBH and mean tree height. Sometimes, the original volume obtained from outside bark diameter calculations and adjusted for missing top volume was higher than the volume obtained from growth and yield tables, in which case the larger number was used in original mass calculations.

Original total mass was calculated by two methods. When literature values for undecayed density were available (Borovikov and Ugolev 1989), they were used as the initial density, and the total mass was determined as a product of overall total tree volume and this undecayed density. In most cases, however, the original total mass was obtained from two freshly cut live trees by first, calculating the bark and wood mass of each bole segment

as a product of segment volume and cross-section density, and then summing the mass of the segments.

The percent mass remaining was calculated for each log and snag as:

$$\% \text{Mass remaining} = \frac{\text{Current Mass}}{\text{Original Mass}} * 100\%$$

3.5 STATISTICAL ANALYSIS

3.5.1 Decay class-specific density

The raw data set for the analysis of decay class-specific density included a total of 970 observations representing 8 regions, 14 species, and 5 decay classes defined by fragmentation and biotic indicators, and two positions reflecting the physical situation of a dead tree: snag (standing dead) or log (laying on the ground).

Sample sizes varied among regions, species, decay classes, and positions leading to an unbalanced design. Several factors contributed to this situation. First, not all species were present in each region. Second, the difficulty in locating and identifying logs in advanced decay classes led to smaller sample sizes or the absence of observations in decay classes four and five. Third, snags were often absent in the advanced decay classes, and where present, were not as abundant as logs. To balance the sample sizes for the categories, I combined some of the regions. Specifically, Moscow oblast' and Nizhnii Novgorod oblast' were combined into a region representing the Central European part of Russia, and Novosibirsk oblast' was combined with Tomskaya oblast' into a region representing the West-Siberia Region. Moreover, species of the same

genera were combined. *Larix dahurica* and *Larix siberica* were combined into LARC, representing *Larix* spp. *Picea abies*, *Picea obovata*, and *Picea ajanensis* were combined into SPRU, representing *Picea* spp. *Pinus siberica* and *Pinus koraiensis* were combined into KEDR, representing a group of Russian white pines. The observations for *Quercus* spp. were removed due to the small sample size (N=7). As a result, the intermediate data set had total of 963 observations, organized by 6 regions, 8 species, 5 decay classes, and 2 positions.

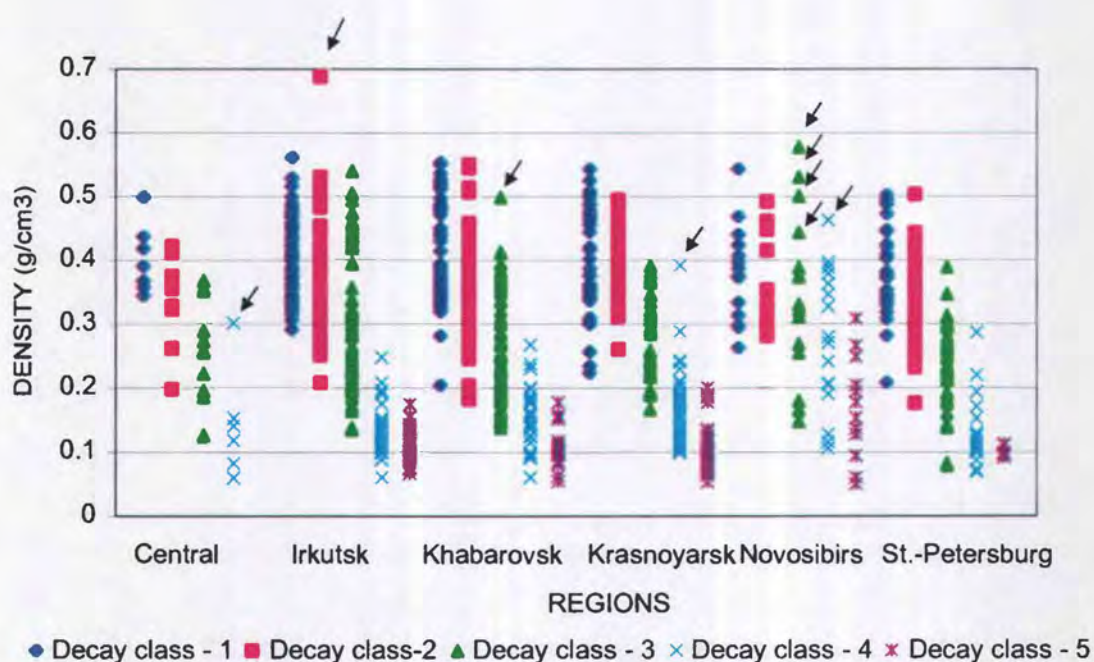
Before proceeding with the analysis, the data were plotted and examined for outliers (Figure 3-2). Nine such observations were detected, and after careful examination, the decision was made to remove all potential outliers (Appendix 6). After the outliers were removed, the final data set contained 945 observations.

The first step of the analysis was aimed at determining which of the variables (decay class, species, region, and position) or group of variables had a significant effect on density at the alpha 0.05 level. A stepwise regression (GLM PROCEDURE) was run for this purpose (SAS Institute 1990, Ramsey and Schafer 1997, Huso 2000, personal communication). The CLASS statement was applied to categorical variables STUDYID, SPECIES, and POSITION in this analysis.

Based on the results of this first analysis, a second analysis was used to compare the estimates of mean density among all decay classes within each species as well as make a comparison of the estimates of mean density among the species within each decay class. For this analysis, the GLM PROCEDURE was run with LSMEANS statement for uneven sample sizes and Tukey-Kramer p-value adjustment for multiple comparisons at alpha level of 0.05 (SAS Institute 1990, Ramsey and Schafer 1997, Huso 2000, personal communication). The second analysis also included the comparison of the estimates of mean density between logs and snags within each decay class, species, and region, as well as a comparison of

the estimates of mean density among the regions within each decay class, species, and position.

Figure 3-2. Distribution of log density observations over the regions with potential outliers pointed out with an arrow



The comparison of the estimates of mean density between logs and snags for each species within decay class and region was done using a T-TEST. GLM PROCEDURE with LSMEANS statement for uneven sample sizes and Tukey-Kramer p-value adjustment for multiple comparisons at alpha level of 0.05 was used to compare the estimates of mean density among the regions within each species, decay class and position (SAS Institute 1990, Ramsey and Schafer 1997, Huso 2000, personal communication).

3.5.2 Multivariate analysis of CWD visual characteristics

Multivariate analysis was used to analyze the changes in CWD visual characteristics occurring as a result of the decomposition process. Multivariate analysis, also called data reduction, allows one to summarize a large number of observations into a few numbers and to express many interrelated response variables in a more compact way (McCune 1999). As a result of this analysis we get “a quantitative synthetic variable (ordination)” (McCune 1999), in our case, a decomposition gradient, which is produced by “re-expressing continuous change” occurring in log and snag visual characteristics.

For the purpose of this analysis, data were represented in two matrices. The so-called “Qualitative” matrix was 970 rows by 21 columns in size with each row representing a sampling unit (log or snag of a particular species and decay class) and each column representing a visual CWD characteristic (Appendix 7). The “Quantitative” matrix was 970 rows by 5 columns in size with each row representing sampling unit and each column representing species, age, decay class, density, and percent bark cover (Appendix 7). This matrix contained a mix of categorical variables (decay classes and log/snag tree species) that were used for overlays on the ordination, as well as quantitative variables (percent bark cover on bole, decomposition time, and density) that were used for correlations with ordination axes (McCune 1999). The only transformation applied to the data set was dividing the bark cover in the “Qualitative” matrix by 100 (McCune 2000, personal communication) as this improved the coefficient of variation of column totals by putting all variables in this matrix on an equal zero-to-one footing.

PC-ORD (McCune and Mefford 1999) outlier analysis was used to check for potential outliers. Thirty such observations were found that were more than two standard deviations from the centroid, but only nine of those

(Appendix 6) were removed. These nine observations had incomplete records of CWD biotic and fragmentation indicators as well as potentially non-reliable information about these indicators. The final data set had 961 observations.

Non-metric Multidimensional Scaling (NMS) analysis with rotation of the axes was performed. We decided to use NMS, as it performs better than other ordination methods with non-linear distributions and the multiple zeroes common for presence/absence data. Rotation of the axes eased interpretation of strongest gradient and more clearly revealed patterns in the data distribution with decay class and species overlays from the “Quantitative” matrix.

Numerous preliminary runs were done on the data set with different levels of thoroughness. Due to a lack of significant differences between the results of those runs (number of axes suggested and correlation of variables to the scores on the strongest gradient), the Quick and Dirty Autopilot mode was considered as having an appropriate level of thoroughness. The PC-ORD settings for this mode included a maximum number of iterations of 75, instability criterion of 0.001, starting number of axes of 3, number of real runs of 5, and number of randomized (Monte Carlo) runs of 20. The Sorensen distance measure was used. The final NMS run was set to use two dimensions, no step-down in dimensionality, one real run, and no Monte Carlo test (randomized runs).

3.5.3 Decomposition rate-constants

The raw data set for the analysis of decomposition rate-constants included a total of 693 observations representing six regions, eleven species, and two positions (i.e., snag and log). The sample sizes varied among regions, species, and positions leading to an unbalanced design. The observations collected in Novgorod and Novosibirsk were removed due

to a small sample size (N=2 in each), as were observations of *Populus tremula* for the same reason (N=5). As a result, the intermediate data set was created that had total of 684 observations, organized by 4 regions, 10 species, and 2 positions.

Before proceeding with the analysis, a regression was run for each species, region, and position of percent mass remaining versus decomposition time, and the plots of residual versus predicted values were examined for outliers. Decomposition time is the time elapsed from the date of tree death to the date of tree sampling. Two potential outliers were found (Appendix 6) which were snags that had low wood density at an early stage of decomposition. In both cases this low density was the result of heart rot that was probably present when the trees were still alive. These two observations were removed, thus leaving the final data set with 682 observations.

The first step of the analysis was aimed at determining which of the variables or group of variables had a significant effect on percent mass remaining at the 0.05 alpha level. A stepwise regression (GLM PROCEDURE) on untransformed data was run for this purpose (Huso 2000, personal communication). The CLASS statement was applied to the categorical variables STUDYID, SPECIES, and POSITION.

The second step of the analysis was used to determine the coefficients of the exponential equation (Olson, 1963) describing the decomposition process for the sampled species in each region:

$$Y_t = Y_0 * e^{-k*t}, \text{ where}$$

Y_t is the percent density remaining at time t (years), Y_0 is the initial mass in percent dry weight, and k is decomposition rate per year constant (year^{-1}).

As the initial mass of each dead tree varied, we used the percent mass remaining instead of mass as the dependent variable. Percent mass remaining was calculated as:

$$\% \text{ Mass remaining} = \frac{MASS_t}{MASS_0}, \text{ where}$$

$MASS_t$ – mass remaining at time t (years), and $MASS_0$ – the initial mass.

Linear regression (PROC REG procedure) was run after percent mass remaining was transformed to natural logarithms:

$$\ln(\% \text{ Mass remaining}) = -k * t$$

In the third step of the analysis, the decomposition rate constants were examined for differences using the “comparison of regression lines” procedure regressing the percent mass remaining by regions (CLASS statement was applied to region variable) over decomposition time. The significance of differences was determined at the 0.05 alpha level. A similar procedure was applied to the comparison of decomposition rates of logs and snags. The log decomposition rates of different species within each region were visually compared to determine any general patterns in species decomposition rates distribution that might be seen among the regions.

The fourth step of the analysis was executed to determine percent per year decomposition rate constants for a comparison with those obtained earlier for the Russian Northwest region in previous years (Krankina and Harmon 1995). For this purpose, the regression line of each species, region, and position was forced through an intercept of 100%, and the decomposition rate constants were calculated.

In the fifth step of the analysis the decomposition rate constants were calculated using density percent remaining as opposed to mass percent remaining in the step two of the analysis. The main reason for this analysis was to compare the decomposition rates calculated via two methods, one with volume loss over time incorporated into the calculations (mass percent remaining) and the other one without it (density percent remaining).

Finally, we examined if any of the species we studied showed a departure from the single exponential curve. Three such species were identified, namely *Betula costata*, *Picea ajanensis*, and *Pinus koraiensis*. For these species the decomposition process was divided into three phases based on decomposition time and percent mass loss. Then, we fitted a simple exponential regression for each phase of each species and determined the regression coefficients.

3.6 RESULTS

3.6.1 Decay-class specific density

A gradual decrease in mean density from decay class one to decay class five was observed in all species except *Abies siberica* (Figure 3-3). In addition, species became more similar in density as decay class increased (Figure 3-3).

All of the independent variables (decay class, species, position, region), including most of their interactions, had significant effect on decay-class density with p-values ranging from 0.0001 to 0.0068. As expected, decay class explained the most variation in density - 68.0%. Species was the next most important factor explaining an additional 6.1% of the variation. The interaction term of decay class*species explained an

additional 7.1% of the variation, indicating that differences among decay classes varied from species to species. Thus, decay, species, and their interaction together explained 81.2% of the variation associated with wood density. This indicates that separation of CWD by decay class and species would give satisfactory estimates of mean density for the purpose of carbon stores calculations in the forests of Russia. Based on this result, a table containing the estimates of mean specific density (g/cm^3) and standard errors organized by decay class and species was constructed (Table 3-2).

Figure 3-3. Estimates of mean specific density with error bars plotted against species by decay class

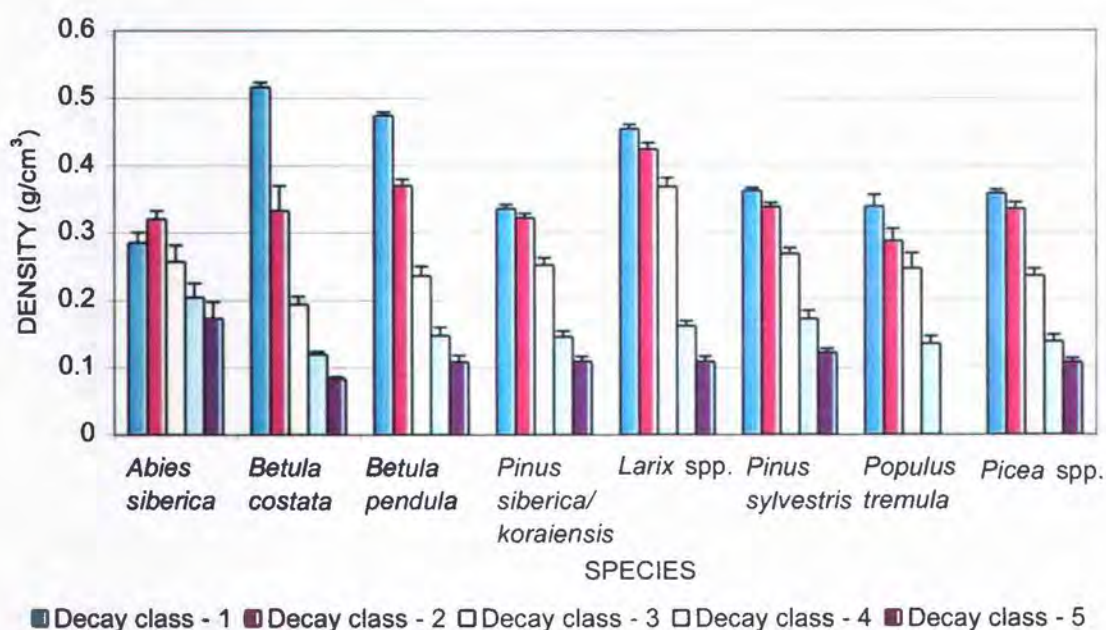
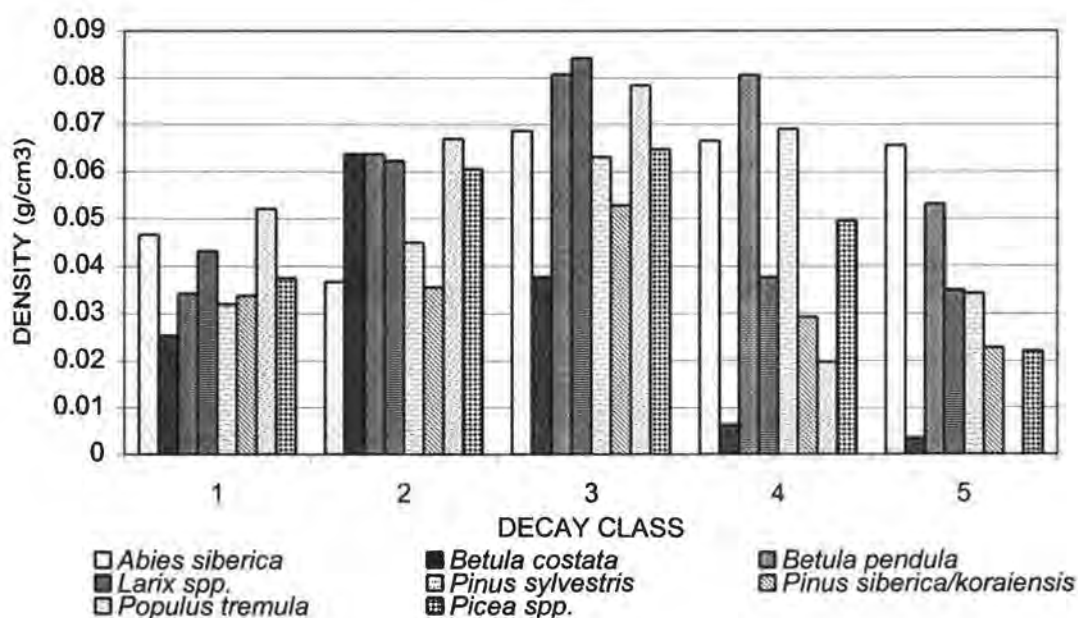


Table 3-2. Mean densities (g/cm³) and SE's (in parenthesis) of CWD by decay class and species for major tree species of Russia

Decay classes	Species							
	<i>Abies siberica</i>	<i>Betula costata</i>	<i>Betula pendula</i>	<i>Larix</i> spp.	<i>Pinus sylvestris</i>	<i>P. siberica/ koraiensis</i>	<i>Populus tremula</i>	<i>Picea</i> spp.
1	0.285 (0.016)	0.516 (0.007)	0.474 (0.005)	0.455 (0.007)	0.362 (0.005)	0.336 (0.006)	0.339 (0.017)	0.358 (0.006)
2	0.320 (0.012)	0.333 (0.037)	0.370 (0.009)	0.424 (0.009)	0.338 (0.006)	0.322 (0.006)	0.287 (0.019)	0.335 (0.010)
3	0.257 (0.024)	0.194 (0.012)	0.237 (0.014)	0.368 (0.013)	0.269 (0.009)	0.252 (0.011)	0.247 (0.023)	0.236 (0.010)
4	0.204 (0.021)	0.120 (0.005)	0.148 (0.012)	0.162 (0.008)	0.172 (0.012)	0.146 (0.008)	0.135 (0.011)	0.139 (0.010)
5	0.173 (0.025)	0.084 (0.003)	0.108 (0.010)	0.109 (0.008)	0.122 (0.006)	0.109 (0.007)	N/A	0.108 (0.006)

When the standard deviations of the estimates of mean density of each species were plotted over decay classes (Figure 3-4), the standard deviations increased and reached maximum in decay class three, and then, declined towards decay class five.

Figure 3-4. Standard deviation of mean density per decay class by species



As decay class and species were two most significant factors in explaining variation in density, I compared the estimates of the mean density 1) among decay classes within each species and 2) among the species within each decay class. The first comparison indicated that there was an overlap of the adjacent decay classes especially for decay classes one and two and for decay classes four and five (Table 3-3). The second comparison showed the differences of the estimates of mean density

Table 3-3. Comparison of the estimates of mean density among decay classes within each species

Decay Class	Species															
	<i>Abies siberica</i>		<i>Betula costata</i>		<i>Betula pendula</i>		<i>Pinus siberica/ koraiensis</i>		<i>Larix spp.</i>		<i>Pinus sylvestris</i>		<i>Populus tremula</i>		<i>Picea spp.</i>	
	Mean	Tukey grouping	Mean	Tukey grouping	Mean	Tukey grouping	Mean	Tukey grouping	Mean	Tukey grouping	Mean	Tukey grouping	Mean	Tukey grouping	Mean	Tukey grouping
1	0.285	A	0.516	A	0.474	A	0.336	A	0.455	A	0.362	A	0.339	A	0.358	A
2	0.320	A	0.333	B	0.370	B	0.322	A	0.424	A	0.338	A	0.287	AB	0.335	A
3	0.257	AB	0.194	C	0.237	C	0.252	B	0.368	B	0.269	B	0.247	BC	0.236	B
4	0.204	B	0.120	CD	0.148	D	0.146	C	0.162	C	0.172	C	0.135	C	0.139	C
5	0.173	B	0.084	D	0.108	D	0.109	C	0.109	D	0.122	D	N/A	N/A	0.108	C

observed among species in early decay classes decrease as the decomposition process progresses from decay class one to decay class five (Table 3-4). In fact, no statistically significant differences were observed among decay class four specific densities.

Because position (snag vs. log) and region (STUDYID) were significantly contributing to explaining variation in wood density in the regression model (p-values of 0.0001), I ran an analysis to compare the estimates of the mean density 1) between logs and snags within each decay class, species, and region, and 2) among the regions within each decay class, species, and position. This indicated that mean density of logs and snags in decay class one do not differ for most species or regions. Birch did not show any difference in mean density among logs and snags for any decay class or region. Conifers such as larch, spruce, and Siberian or Korean white pine did not show differences in mean density in decay class one, but did exhibit differences in decay classes two and three (Appendix 5). Also, there were no significant differences among the estimates of mean density of CWD sampled in different regions (Appendix 5).

Table 3-4. Tukey comparison of the estimates of mean density among species within each decay class

		Species							
Decay Class		<i>Abies siberica</i>	<i>Betula costata</i>	<i>Betula pendula</i>	<i>Pinus siberica/koraiensis</i>	<i>Larix</i> spp.	<i>Pinus sylvestris</i>	<i>Populus tremula</i>	<i>Picea</i> spp.
1	Mean	0.285	0.516	0.474	0.336	0.455	0.362	0.339	0.358
	Tukey grouping	A	B	C	D	C	D	D	D
2	Mean	0.320	0.333	0.370	0.322	0.424	0.338	0.287	0.335
	Tukey grouping	AB	ABC	A	B	C	AB	B	AB
3	Mean	0.257	0.194	0.237	0.252	0.368	0.269	0.247	0.236
	Tukey grouping	AB	A	AB	AB	C	B	AB	AB
4	Mean	0.204	0.120	0.148	0.146	0.162	0.172	0.135	0.139
	Tukey grouping	A	A	A	A	A	A	A	A
5	Mean	0.173	0.084	0.108	0.109	0.109	0.122	N/A	0.108
	Tukey grouping	A	AB	BC	BC	BC	AC	N/A	BC

3.6.2 Multivariate analysis of CWD visual characteristics

Multivariate analysis performed with untransformed data showed an arch pattern associated with high variability in the data. The transformation summary indicated that division of bark cover percent by 100 not only decreased the variability in row and column totals as indicated by the CV of sums, but also decreased average skewness in rows (Table 3-5). Putting all the variables in the “Qualitative” matrix on zero-to-one footing was important because NMS analysis has tendency to assign higher correlation scores to the variables with larger numerical values. Since the “Qualitative” matrix contained combination of binary variables having values 0 and 1, and percent bark cover on bole variable ranging from 0 to a 100 (Appendix 7), the transformation was required to avoid this problem.

Table 3-5. Data transformation summary sheet

Parameter	Before	After
ROWS	961	961
Average skewness	3.465	0.570
CV of sums	71.52	28.34
COLUMNS	21	21
Average skewness	0.637	0.637
CV of sums	397.93	43.86

A scree-plot (Figure 3-5) and the Monte Carlo (random) stress results (Table 3-6) of a preliminary run indicated that a two-dimensional solution was the most appropriate for these data.

Figure 3-5. Scree-plot of stress in relation to dimensionality

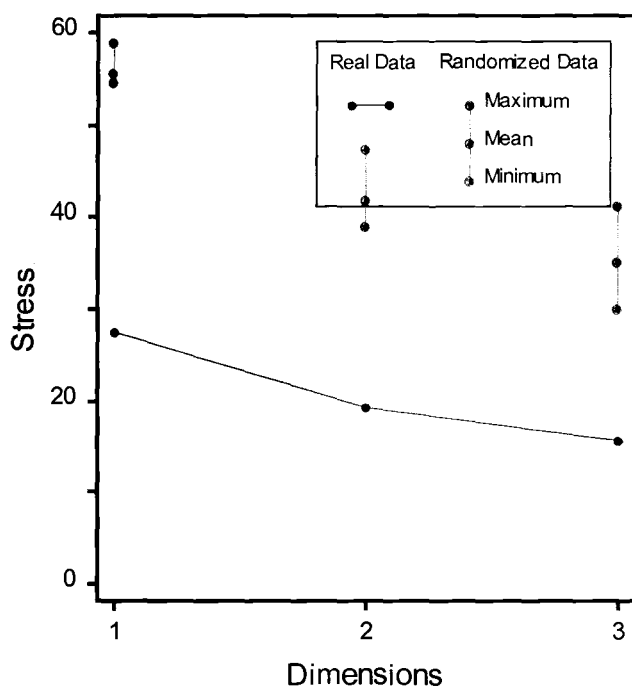


Table 3-6. Stress in relation to dimensionality (number of axes)

Axes	Stress in real data 5 run(s)			Stress in randomized data Monte Carlo test, 20 runs			p
	Minimum	Mean	Maximum	Minimum	Mean	Maximum	
1	27.572	45.823	56.162	54.643	55.779	58.932	0.0476
2	19.316	20.192	21.132	39.131	41.827	47.484	0.0476
3	15.551	18.996	28.973	30.035	35.100	41.234	0.0476

p - proportion of randomized runs with stress < or = observed stress
i.e., $p = (1 + \text{no. permutations} \leq \text{observed}) / (1 + \text{no. permutations})$

The axes rotation to one degree resulted in the first axis having the higher coefficient of determination (r^2) of the two (Table 3-7). The first axis

explained 87.8 percent of the variance in the data. This axis rotation also led to an increased correlation between the variables from the “Qualitative” matrix and scores on the first ordination axis (Table 3-8). Variables associated with early stages of decomposition (bark on bole, bark on branches, branches, and twigs) had lower scores, whereas variables associated with late stages of decomposition (heartwood friable, sapwood sloughing, and sapwood friable) had higher axis scores. Variables from the “Quantitative” matrix had a strong correlation with the ordination axis one (Table 3-9) with density being negatively correlated to axis one, decreasing as scores on the first ordination axis increased. Decomposition time was also positively correlated to axis one, having higher scores on the ordination axis one with older logs and snags. These correlations as well as an overlay of variables from “Quantitative” matrix on “Qualitative” matrix with decay class as a grouping variable (Figure 3-6) all support the idea that the first ordination is a decomposition gradient. Clusters of points representing decay classes are distributed along this ordination axis in increasing sequence of decay classes, with vectors representing increasing density and bark cover pointed towards beginning of coordinates and increasing decomposition time (age) having opposite direction. The distribution of the observations in the ordination shows intermixing of decay class one and two and decay class four and five observations. Thus, there were only three distinctive clusters.

Table 3-7. Coefficients of determination for the correlations between ordination distances and distances in the original n-dimensional space

Axis	Increment	Cumulative
1	0.734	0.734
2	0.101	0.836

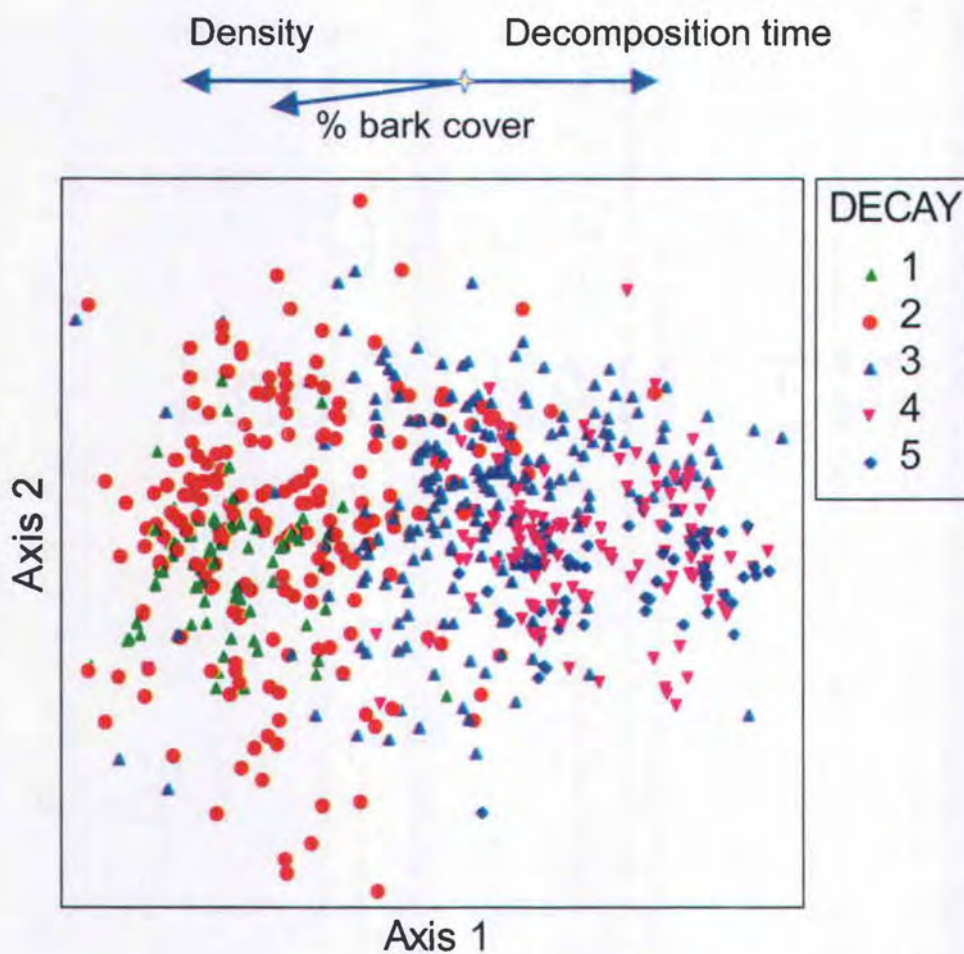
Table 3-8. Variables in the approximate sequence of their appearance and correlation coefficients between them and scores on the ordination axes

Variables	Axis 1	Variables	Axis 2
BARKBOLE	-0.746	BARKBR	-0.312
BARKBR	-0.733	TWIGS	-0.299
BRANCHES	-0.716	NEEDLES	-0.261
TWIGS	-0.700	BRANCHES	-0.215
BCOVER	-0.648	SCATTER	-0.177
NEEDLES	-0.459	BCOVER	-0.172
BEETLES	-0.393	COLLAPSE	-0.138
WOODBORER	-0.129	HWFRIAB	-0.082
CONKS	-0.109	STUBSMOV	-0.065
LICHENS	0.073	BROWNROT	-0.028
ANTS	0.115	BARKBOLE	-0.018
CASEHARD	0.211	CASEHARD	-0.01
WHITEROT	0.464	MOSS	0.073
STUBSMOV	0.623	LICHENS	0.078
SCATTER	0.647	SAPFRIAB	0.118
MOSS	0.659	ANTS	0.127
BROWNROT	0.697	CONKS	0.159
COLLAPSE	0.718	SAPSLOUG	0.159
HWFRIAB	0.743	WHITEROT	0.261
SAPSLOUG	0.763	BEETLES	0.346
SAPFRIAB	0.858	WOODBORER	0.381

Table 3-9. Correlation coefficients between the most important variables from "Quantitative" matrix and scores on the ordination axes

Variables	Axis 1	Axis 2
Density	-0.754	-0.011
Bcover	-0.648	-0.172
Age	0.528	0.144

Figure 3-6. Overlay of variables from the "Quantitative" matrix on the "Qualitative" matrix with decay classes as the grouping variable



There were no significant differences among five best-represented species in terms of the variables correlated to the scores on ordination axis one (Table 3-10). However, correlation coefficients of birch bark cover (-0.257) and bark on bole (-0.200) (Table 3-10) were low, and indicate little change in birch bark presence on bole and percent bark cover over the course of decomposition. This contrasts the coniferous species, which have a high correlation of these variables to first ordination axis, with correlation coefficients ranging from -0.635 to -0.801 and from -0.724 to -0.854 for bark cover and bark on bole, respectively. These indicate a decrease in percent bark cover and bark presence on bole for conifers occurring over the course of decomposition. Also, a plot of percent frequency of indicator occurrence (Figure 3-7) suggests that the presence of bark on boles may be the single most important indicator separating birch from all coniferous species. Due to the extended bark presence in birch the presence of characteristics such as beetles, woodborers, conks and their traces (galleries, holes) can be detected in birch in more advanced decay classes than in conifers. The latter lose their bark early in decomposition, so it is almost impossible to detect the presence of these biotic indicators in coniferous logs of decay classes four and five. Also, the difference between birch and conifers was indicated by early occurrence (decay class one) of white rot in birch logs and snags, while in conifers the appearance of this type of rot was recorded for decay classes two, three, four and five.

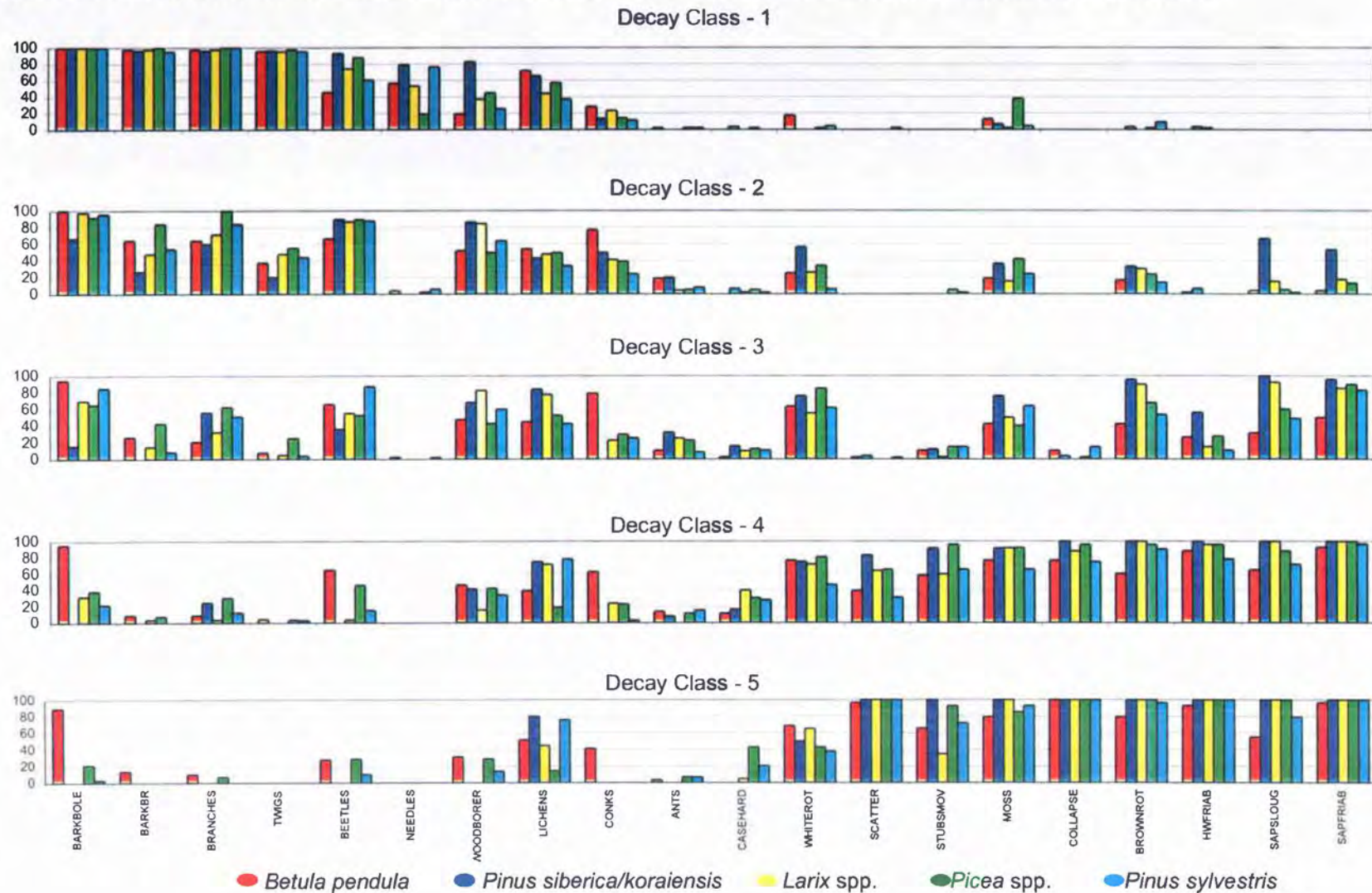
Another difference among the species was the high percent of occurrence of friable sapwood and sapwood sloughing in decay class two CWD of Korean and Siberian pines (Figure 3-7) and low percent of bark on bole occurrence in decay class three of the same species. For example, by decay class two about 60 percent of the white pine CWD pieces sampled had friable sapwood or sapwood sloughing as opposed to less than 20 percent in the other species; and less than 20 percent of the white pine boles had bark present by decay class three, while the bark presence was

Table 3-10. Correlations of indicator variables in ascending order to scores on the ordination axis one for five taxa well represented in the study area

<i>Betula pendula</i>		<i>Pinus siberica/koraiensis</i>		<i>Larix spp.</i>		<i>Picea spp.</i>		<i>Pinus sylvestris</i>	
Variables	r	Variables	r	Variables	r	Variables	r	Variables	r
BRANCHES	-0.817	BARKBOLE	-0.854	BARKBOLE	-0.814	BARKBOLE	-0.724	BARKBOLE	-0.792
BARKBR	-0.799	BARKBR	-0.795	BCOVER	-0.801	BARKBR	-0.702	BRANCHES	-0.776
TWIGS	-0.707	BCOVER	-0.788	BRANCHES	-0.769	BRANCHES	-0.663	BARKBR	-0.708
NEEDLES	-0.435	TWIGS	-0.787	BARKBR	-0.710	BCOVER	-0.635	BCOVER	-0.704
BCOVER	-0.257	BEETLES	-0.739	TWIGS	-0.704	TWIGS	-0.567	TWIGS	-0.694
LICHENS	-0.226	NEEDLES	-0.650	BEETLES	-0.660	BEETLES	-0.496	NEEDLES	-0.519
BARKBOLE	-0.200	BRANCHES	-0.586	NEEDLES	-0.429	NEEDLES	-0.395	BEETLES	-0.435
BEETLES	-0.008	WOODBORER	-0.444	WOODBORER	-0.331	LICHENS	-0.151	WOODBORER	-0.148
ANTS	0.023	CONKS	-0.356	CONKS	-0.214	WOODBORER	-0.113	CONKS	-0.092
WOODBORER	0.038	CASEHARD	0.102	ANTS	0.094	CONKS	-0.100	ANTS	0.148
CONKS	0.075	ANTS	0.166	LICHENS	0.175	ANTS	0.102	CASEHARD	0.272
CASEHARD	0.215	LICHENS	0.259	CASEHARD	0.311	CASEHARD	0.254	WHITEROT	0.404
WHITEROT	0.479	WHITEROT	0.563	STUBSMOV	0.543	WHITEROT	0.441	LICHENS	0.420
BROWNROT	0.496	SCATTER	0.652	WHITEROT	0.544	MOSS	0.477	SCATTER	0.642
MOSS	0.549	COLLAPSE	0.667	SCATTER	0.730	BROWNROT	0.546	STUBSMOV	0.667
STUBSMOV	0.665	STUBSMOV	0.668	MOSS	0.746	SCATTER	0.567	MOSS	0.668
SAPSLOUG	0.669	MOSS	0.703	COLLAPSE	0.766	COLLAPSE	0.617	SAPSLOUG	0.722
SCATTER	0.683	HWFRIAB	0.767	HWFRIAB	0.787	SAPFRIAB	0.638	BROWNROT	0.754
COLLAPSE	0.787	BROWNROT	0.810	BROWNROT	0.834	SAPSLOUG	0.657	HWFRIAB	0.78
HWFRIAB	0.793	SAPSLOUG	0.859	SAPFRIAB	0.862	STUBSMOV	0.680	COLLAPSE	0.797
SAPFRIAB	0.846	SAPFRIAB	0.870	SAPSLOUG	0.874	HWFRIAB	0.686	SAPFRIAB	0.881

r - coefficient of correlation

Figure 3-7. Frequency of an indicator (in percent) occurring in CWD of different decay classes by species



observed on 65 to 95 percent of other species' boles. This pattern in white pines may be explained by the slow decomposition of heartwood of these species. This is consistent with observation that CWD pieces of these species assigned to decay class two have decomposition time ranging from 7 to 65 years (Appendix 3).

The difference among decay classes is represented by the sequence of the appearance of biological and fragmentation indicators in *Pinus sylvestris* CWD (Figure 3-8). Decay class one dead trees have most of their needles, twigs, branches, bark on branches and bole. Some colonization of bole tissues by bark beetles, woodborers, and fungi takes place on this stage.

Decay class two dead trees have occasional needles and branches, and bark on branches is always present. Most of boles in this decay class have bark cover fluctuating between 5 and 50%. Bark beetles, woodborers, and conks become more abundant. Moss covered logs become more common. Some brown rot appears.

Decay class three CWD pieces have no needles, no twigs, most of the branches are still present, but bark is absent. Most of boles in this decay class retain less than 25 percent bark cover. Bark beetles, woodborers and conks or traces of their presence (holes, larval passages) can still be well recognized. All the logs and snags are damaged by brown or white rot and most of them have friable sapwood and sloughing. Most of the logs have some moss cover.

Decay class four logs completely lack needles, twigs, and branches. The presence of bark beetles on this stage is hardly detectable due to bark and sapwood losses. Woodborer galleries, however, are still visible in some logs due to the deeper penetration of their larvae. No conks were detected at this point probably because of their separation from the boles due to the fragmentation process. Presence of lichens and mosses was detected on all logs sampled. All the logs contained either brown or white rot and had friable sapwood and sloughing. Most of the logs had friable heartwood as well, and because of that, branch stubs that could be moved by hand. About 50 percent of these logs appeared to have casehardening, a situation where outer tissues are drier and

Figure 3-8. Results of non-metric multi-dimensional scaling analysis for 201 *Pinus sylvestris* logs and snags

5	4	3	2	1	Decay class
0.599 to 1.425	0.116 to 1.379	-0.779 to 1.132	-1.378 to 0.462	-1.247 to -0.502	Ord. score range
0.199 - 0.068	0.390 - 0.068	0.373 - 0.142	0.419 - 0.238	0.432 - 0.297	Density range
40 - 70	17 - 70	8 - 40	1 - 19	0 - 9	Decomp. time range
30 - 0	10 - 0	90 - 0	100 - 2	100 - 10	Bark cov. % range
					Bark on bole
					Branches
					Bark on branches
					Twigs
					Needles
					Beetles
					Bark cov. 95 - 100%
					Bark cov. 25 - 50%
					Bark cov. 75 - 95%
					Bark cov. 50 - 75%
					Woodborers
					Conks
					Bark cov. 5 - 25%
					Ants
					Casehardening
					White rot
					Lichens
					Moss
					Log scattered
					Br. stubs moving
					Sapwood sloughing
					Brown rot
					Bark cov. 0 - 5%
					Heartwood friable
					Log collapsing
					Sapwood friable

The biotic and fragmentation indicators are distributed according to their correlation to decomposition gradient (ordination axis one)

less decomposed, forming a tube with rotten, more friable tissues inside. In this decay class, most of the logs collapsed due to loss in strength and inability to support their own weight, and some of them were scattered over the soil surface with their cross section being elliptical.

Decay class five logs had lost all needles, twigs, bark on branches, and branches. Bark cover fluctuated from 0 to 5 percent with occasional logs having a higher percent bark cover. All logs in this decay class had some percent of lichens and moss cover and all of them had either white or brown rot present. All logs were collapsing and scattered due to the friability and lack of strength of the sapwood and heartwood. Sapwood sloughing was noted on most of them as well. Branch stubs on decay class five logs were not obvious, because much of the log would disappear due to decomposition, often leaving us with the base of the log lacking the branch stubs. However, when branch stubs were found, they could be easily separated from the stem by hand.

3.6.3 Decomposition rate-constants

The decomposition rate-constants ranged from -0.015 to -0.078 for logs and from -0.077 to +0.020 for snags (Table 3-11). Some differences and some similarities were observed among decomposition rates within each species among the regions as well as within each region among the species. The differences between decomposition rates of logs and snags were fairly high for some species. In general, decomposition rates of logs were higher than those of snags.

All of the independent variables examined (percent mass remaining, decomposition time, position, and region), including some of their interactions, had a significant effect on percent mass remaining with p-values ranging from 0.0001 to 0.0045. As expected, decomposition time explained the most variation in percent mass remaining – 50.3%.

Table 3-11. Coefficients and SE's (in parenthesis) of the regressions of percent mass remaining over decomposition time used to estimate decomposition rate constants for species studied in four regions of Russia from west to east

Species	Regions	Regression coefficients ^a								
		Snags					Logs			
		Y ₀ (%)	k (year ⁻¹)	p-value*	N	Adj. r ²	Y ₀ (%)	k (year ⁻¹)	N	Adj. r ²
<i>Betula pendula</i>	St.-Petersburg	92.68	-0.027 (0.008)	0.0185	7	0.64	100.00	-0.054 (0.013)	11	0.62
	Krasnoyarsk	106.53	-0.056 (0.009)	0.0001	13	0.78	107.08	-0.061 (0.006)	28	0.81
	Irkutsk	108.11	-0.052 (0.009)	0.0001	17	0.67	86.56	-0.042 (0.004)	41	0.75
	Khabarovsk	130.92	-0.077 (0.022)	0.0185	7	0.64	118.73	-0.078 (0.008)	20	0.82
<i>Betula costata</i>	Khabarovsk	108.63	-0.071 (0.003)	0.0001	7	0.99	79.13	-0.030 (0.003)	23	0.81
<i>Picea abies</i>	St.-Petersburg	118.35	-0.044 (0.018)	0.0710	6	0.50	82.48	-0.026 (0.003)	20	0.78
<i>P. obovata</i>	Krasnoyarsk	98.53	+0.0006 (0.0043)	0.8957	8	-0.16	110.58	-0.049 (0.006)	31	0.68
<i>P. ajanensis</i>	Khabarovsk	125.24	-0.035 (0.003)	0.0001	14	0.92	96.59	-0.028 (0.002)	39	0.83
<i>Pinus sylvestris</i>	St.-Petersburg	103.85	-0.037 (0.009)	0.0012	14	0.56	81.76	-0.027 (0.005)	42	0.46
	Krasnoyarsk	97.13	+0.020 (0.011)	0.1121	8	0.26	120.60	-0.044 (0.003)	31	0.85
	Irkutsk	103.25	-0.004 (0.003)	0.2383	19	0.03	111.20	-0.036 (0.003)	35	0.84
<i>Larix siberica</i>	Krasnoyarsk	101.45	-0.004 (0.005)	0.4168	8	-0.04	90.23	-0.023 (0.002)	30	0.85
	Irkutsk	102.49	-0.010 (0.001)	0.0001	28	0.64	99.72	-0.031 (0.002)	42	0.83
<i>Larix dahurica</i>	Khabarovsk	93.56	-0.009 (0.012)	0.4801	10	-0.05	80.70	-0.015 (0.002)	26	0.66
<i>Pinus siberica</i>	Irkutsk	88.02	-0.003 (0.001)	0.0092	17	0.33	88.55	-0.019 (0.002)	33	0.66
<i>P. koraiensis</i>	Khabarovsk	86.66	-0.003 (0.002)	0.3030	12	0.02	86.79	-0.015 (0.001)	35	0.87

^a The regression was of the form $Y_t = Y_0 \cdot e^{-kt}$ where Y_t is the percentage of the mass remaining at time t (years), Y_0 is the initial mass in percent dry weight, and k is the decomposition rate constant

* P-value for the comparison of decomposition-rate constants to zero.

Surprisingly, position was the next most important factor explaining an additional 8.6% of the variation. The interaction term of decomposition time*position was not significant (p-value 0.0771), contributing only 0.1% to the variation explained. Species explained additional 6.4%, while regions explained only additional 0.5% of the variation associated with percent mass remaining. The interaction term decomposition time*species was highly significant (p-value of 0.0001), explaining an additional 8.4 percent of the variation in percent mass remaining, and indicating that differences in percent mass remaining among species increase with time elapsed since tree death.

The intercepts of the exponential equations describing the decomposition process in logs and snags of the studied species in each region fluctuated between 40.96 percent and 130.92 percent. Usually, an intercept below 100 percent indicates a high initial decomposition rate while an intercept above 100 percent indicates a lag in decomposition in the early stages of decay (Harmon et al. 1995). However, for birch in St.-Petersburg region the low intercept Y_0 of 40.96 percent and associated slow decomposition rate coefficient k of -0.011 were probably produced by a small number of birch logs sampled during the first 6 years of log decomposition in that region (Figure 3-9). The equation describing the decomposition process in birch logs of the St.-Petersburg region was therefore modified by forcing the regression through an intercept of 100%. The decomposition rate coefficient of 5.4 percent per year obtained from this analysis was used in the subsequent statistical analysis.

A comparison among the decomposition rate constants within each species and position indicates that some of the decomposition rates were not significantly different from each other at the 0.05 alpha level (Table 3-12). The most similar rates were in the white pine group. The log decomposition rate of *Pinus siberica* was not different from the log decomposition rate of *Pinus koraiensis* (p-value of 0.1355), as snag

decomposition rate of *Pinus siberica* was not different from snag decomposition rate of *Pinus koraiensis* (p-value of 0.837).

The decomposition rates of logs were in general higher than those of snags for larch and white pine, whereas for birch the decomposition rates of logs and snags were similar (Table 3-11). Although, all of the species had decomposition rates calculated for logs and snags, we decided to make a comparison between decomposition rates of logs and snags only for species and regions with similar decomposition time range of sampled pieces of CWD (Table 3-13), specifically *Picea ajanensis* in Khabarovsk region, and *Pinus siberica* and *Larix siberica* in Irkutsk region (Figure 3-10). This indicates that while decomposition rates of logs and snags are not significantly different for *Picea ajanensis* (p-value of comparison 0.121), they are different for *Pinus siberica* and *Larix siberica* (p-values of 0.002 and 0.001, respectively).

Figure 3-9. *Betula pendula* logs collected in the St.-Petersburg region for decomposition rate calculations

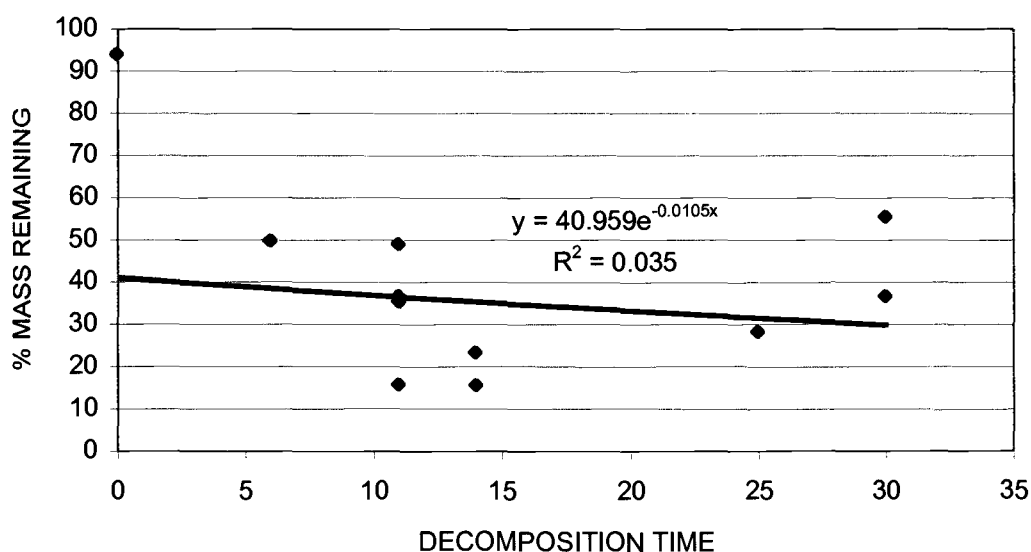


Table 3-12. Decomposition rate comparisons (SE's for the comparison in parenthesis) based on species group runs, indicating the differences and similarities of the decomposition rates among the regions within each species

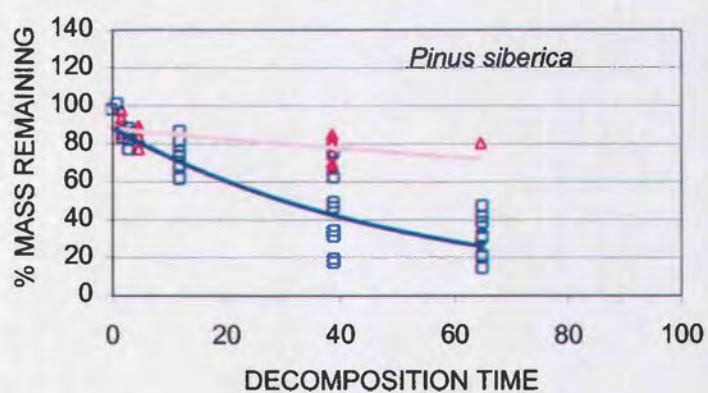
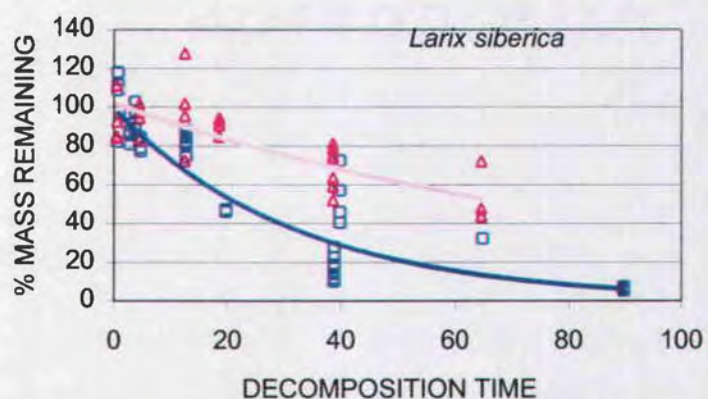
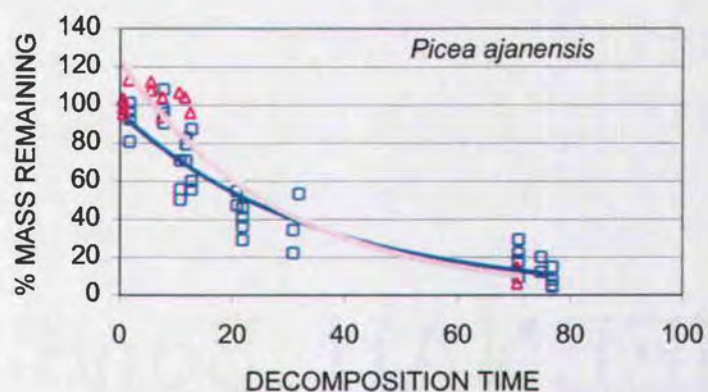
Species	Regions	Snags	Grouping*		Logs	Grouping*	
			0.05	0.01		0.05	0.01
<i>Betula pendula</i>	St.-Petersburg	-0.027 (0.017)	A	A	-0.054 (0.013)	AB	AB
	Krasnoyarsk	-0.056 (0.007)	AB	A	-0.061 (0.006)	A	AB
	Irkutsk	-0.052 (0.014)	AB	A	-0.042 (0.004)	B	B
	Khabarovsk	-0.077 (0.014)	B	A	-0.078 (0.009)	A	A
<i>Betula costata</i>	Khabarovsk	-0.071 (0.003)	N/A	N/A	-0.030 (0.003)	N/A	N/A
<i>Picea abies</i>	St.-Petersburg	-0.044 (0.037)	AB	AB	-0.026 (0.005)	A	A
<i>Picea obovata</i>	Krasnoyarsk	+0.0006 (0.011)	B	B	-0.049 (0.006)	B	B
<i>Picea ajanensis</i>	Khabarovsk	-0.035 (0.002)	A	A	-0.028 (0.002)	A	A
<i>Pinus sylvestris</i>	St.-Petersburg	-0.037 (0.007)	A	A	-0.027 (0.003)	A	A
	Krasnoyarsk	+0.020 (0.027)	AB	AB	-0.044 (0.005)	B	B
	Irkutsk	-0.004 (0.003)	B	B	-0.036 (0.004)	AB	AB
<i>Larix siberica</i>	Krasnoyarsk	-0.004 (0.007)	A	A	-0.023 (0.002)	A	A
	Irkutsk	-0.010 (0.001)	A	A	-0.031 (0.002)	B	B
<i>Larix dahurica</i>	Khabarovsk	-0.009 (0.013)	A	A	-0.015 (0.003)	C	A
<i>Pinus siberica</i>	Irkutsk	-0.003 (0.002)	A	A	-0.019 (0.002)	A	A
<i>Pinus koraiensis</i>	Khabarovsk	-0.003 (0.001)	A	A	-0.015 (0.001)	A	A

* Same letter within a species indicates a lack of significant differences among the regional decomposition rates at different alpha levels

Table 3-13. Decomposition time range of sampled logs and snags in different regions

Species	Regions	Snag	Log
<i>Betula pendula</i>	St.-Petersburg	0 – 12	0 – 30
	Krasnoyarsk	0 – 15	0 – 29
	Irkutsk	1 – 8	1 – 33
	Khabarovsk	2 – 15	0 – 27
<i>Betula costata</i>	Khabarovsk	1 – 13	2 – 77
<i>Picea abies</i>	St.-Petersburg	2 – 7	2 – 73
<i>Picea obovata</i>	Krasnoyarsk	2 – 15	0 – 33
<i>Picea ajanensis</i>	Khabarovsk	1 – 71	2 – 77
<i>Pinus sylvestris</i>	St.-Petersburg	1 – 13	0 – 70
	Krasnoyarsk	0 – 4	0 – 45
	Irkutsk	1 – 19	1 – 42
<i>Larix siberica</i>	Krasnoyarsk	0 – 15	0 – 110
	Irkutsk	1 – 65	1 – 90
<i>Larix dahurica</i>	Khabarovsk	8 – 19	0 – 104
<i>Pinus siberica</i>	Irkutsk	2 – 65	0 – 65
<i>Pinus koraiensis</i>	Khabarovsk	1 – 31	0 – 160

Figure 3-10. *Picea ajanensis*, *Larix siberica*, and *Pinus siberica* exponential curves describing log and snag decomposition



Legend: □ Logs △ Snags --- Exponent. (Logs) --- Exponent. (Snags)

The species ranking by their decay resistance indicate that birch is the fastest decaying species, usually followed by spruce and pine, with larch and white pine being the most decay resistant species (Figure 3-11). This pattern holds for all species and regions sampled as indicated by CWD half-life, and time required for 95 and 99% of the mass to decompose (Table 3-14).

Figure 3-11. The general pattern of mass percent remaining distribution over decomposition time for five species in Khabarovsk region

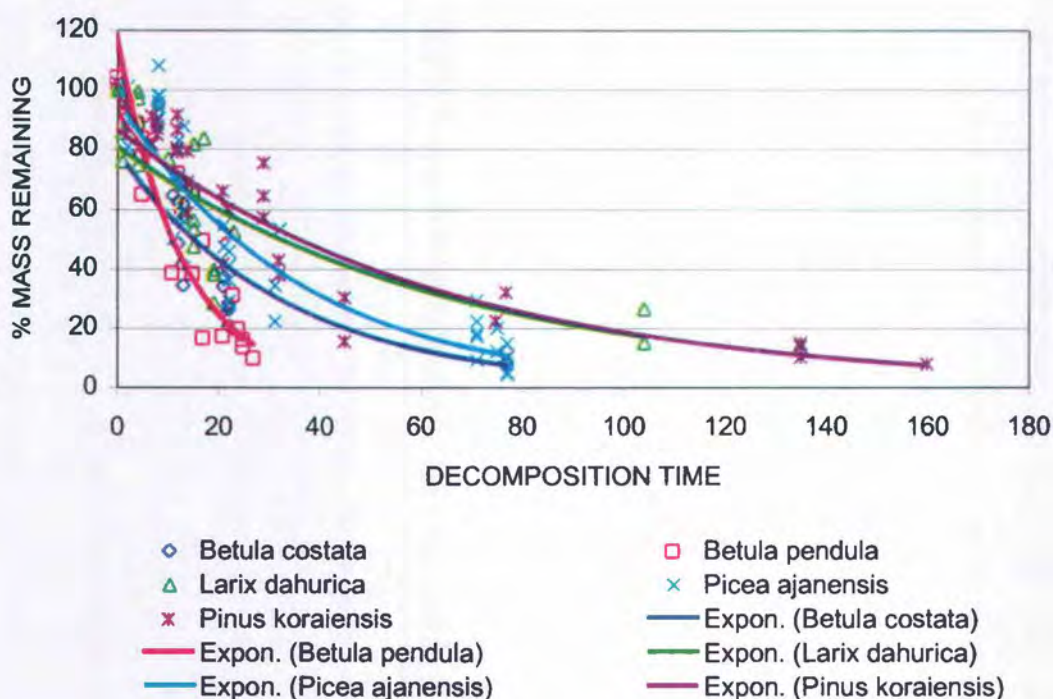


Table 3-14. Time periods (years) required for a given percent of mass to decompose

Regions	Species	50% mass	95% mass	99% mass
St.-Petersburg	<i>Betula pendula</i>	13	55	85
	<i>Pinus sylvestris</i>	18	103	163
	<i>Picea abies</i>	19	108	170
Krasnoyarsk	<i>Betula pendula</i>	12	50	77
	<i>Picea obovata</i>	16	63	96
	<i>Pinus sylvestris</i>	20	72	109
	<i>Larix siberica</i>	26	126	196
Irkutsk	<i>Betula pendula</i>	13	68	106
	<i>Pinus sylvestris</i>	22	86	131
	<i>Larix siberica</i>	22	97	148
	<i>Pinus siberica</i>	30	151	236
Khabarovsk	<i>Betula pendula</i>	11	41	61
	<i>Betula costata</i>	15	92	146
	<i>Picea ajanensis</i>	24	106	163
	<i>Larix dahurica</i>	32	185	293
	<i>Pinus koraiensis</i>	37	190	298

Birch showed no difference in decomposition rates calculated using percent mass remaining versus percent density remaining (Figure 3-12). Conifers, on the other hand (*Pinus koraiensis*, as an example), do exhibit these differences with lower decomposition rates when calculated without account for fragmentation loss (Figure 3-13).

Betula costata, *Picea ajanensis*, and *Pinus koraiensis* (Figure 3-14) showed a departure in their decomposition from a single exponential curve. The duration of each phase varied among the species and was 8, 8, and 12 years for the phase one, 14, 24, and 33 for the phase two, and 55, 45, and 115 for the phase three for birch, spruce, and pine, respectively. The

Figure 3-12. Comparison of regression lines of *Betula pendula* decomposition rates calculated using percent mass remaining versus percent density remaining

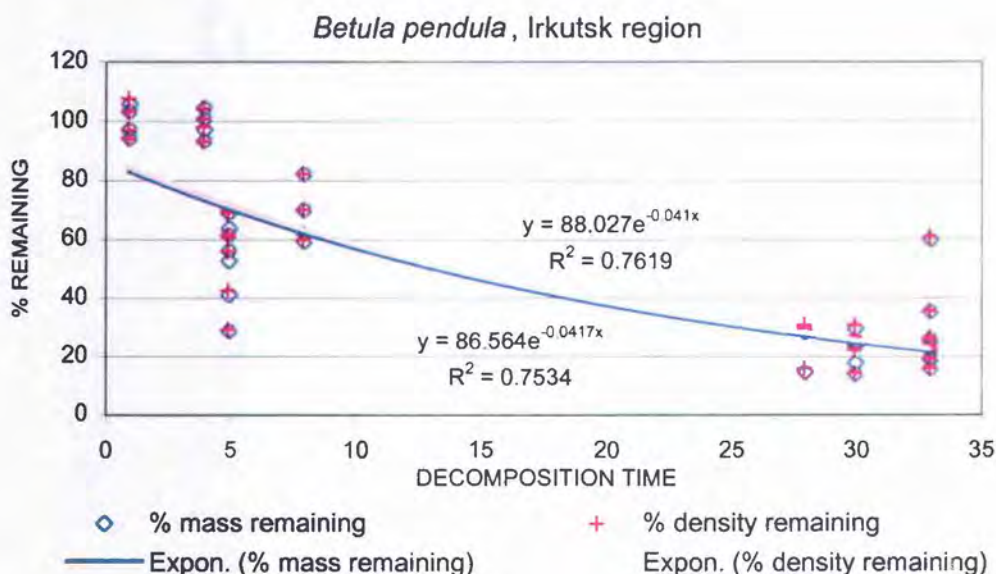


Figure 3-13. Comparison of regression lines of *Pinus koraiensis* for decomposition rates calculated using percent mass remaining versus percent density remaining

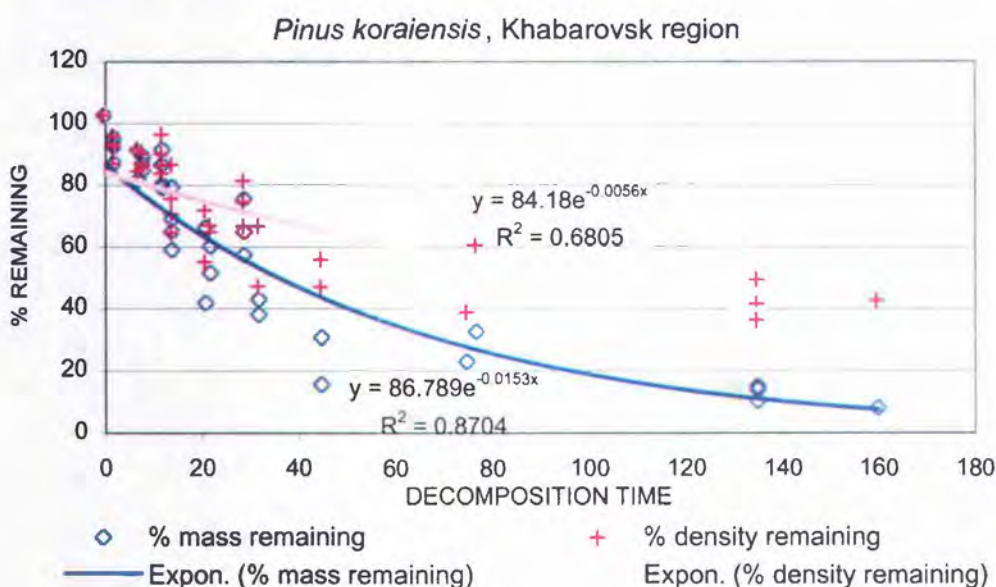
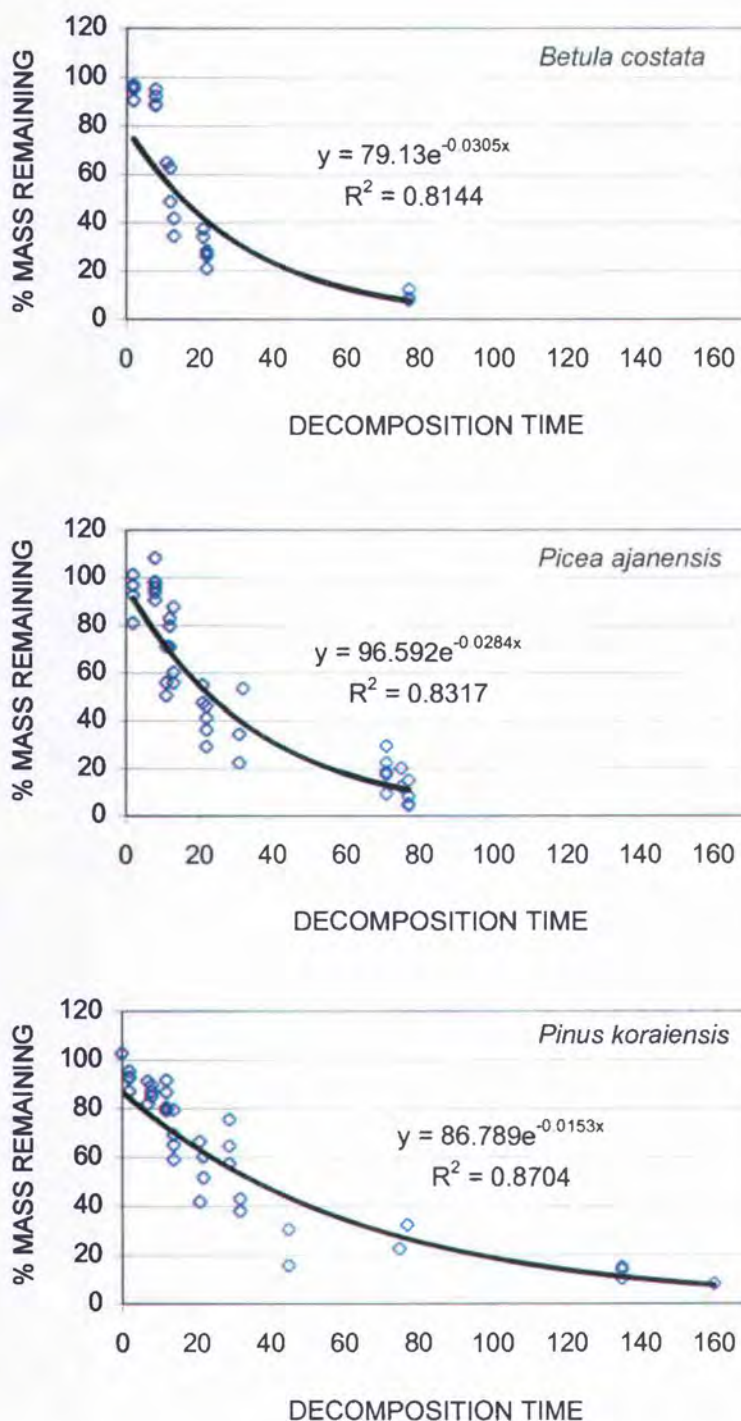


Figure 3-14. *Betula costata*, *Picea ajanensis*, and *Pinus koraiensis* mass loss as represented by a single negative exponential curve



decomposition in the first phase was slow for pine and no changes were observed for birch and spruce. The second phase was rapid for all three species, and followed by moderately slow phase for birch and spruce and very slow for pine (Figure 3-15). This approach also indicated that among these three species birch is the least decay resistant and pine is the most decay resistant with spruce in the middle, based on the decomposition rate of the phase 2 (Table 3-15).

Temperature and amount of precipitation exhibited no obvious correlation with decomposition rates of the studied species. However, a positive correlation of decomposition rates to temperature and precipitation was observed when decomposition rates of *Betula pendula* were plotted against the degree-days (sum of annual $T^{\circ}\text{C}>5$) and precipitation sum over the period with $T^{\circ}\text{C}>5$ (Figure 3-16). The decay resistant species (*Larix* spp. and *Pinus siberica/koraiensis*) showed a negative correlation in relation to the sum of precipitation over the period with $T^{\circ}\text{C}>5$. No correlation with the degree-days, however, was detected for *Larix* spp. and *Pinus siberica/koraiensis* or any other coniferous species in our study.

Figure 3-15. *Betula costata*, *Picea ajanensis*, and *Pinus koraiensis* fitted with separate exponential curves indicating three phases in decomposition

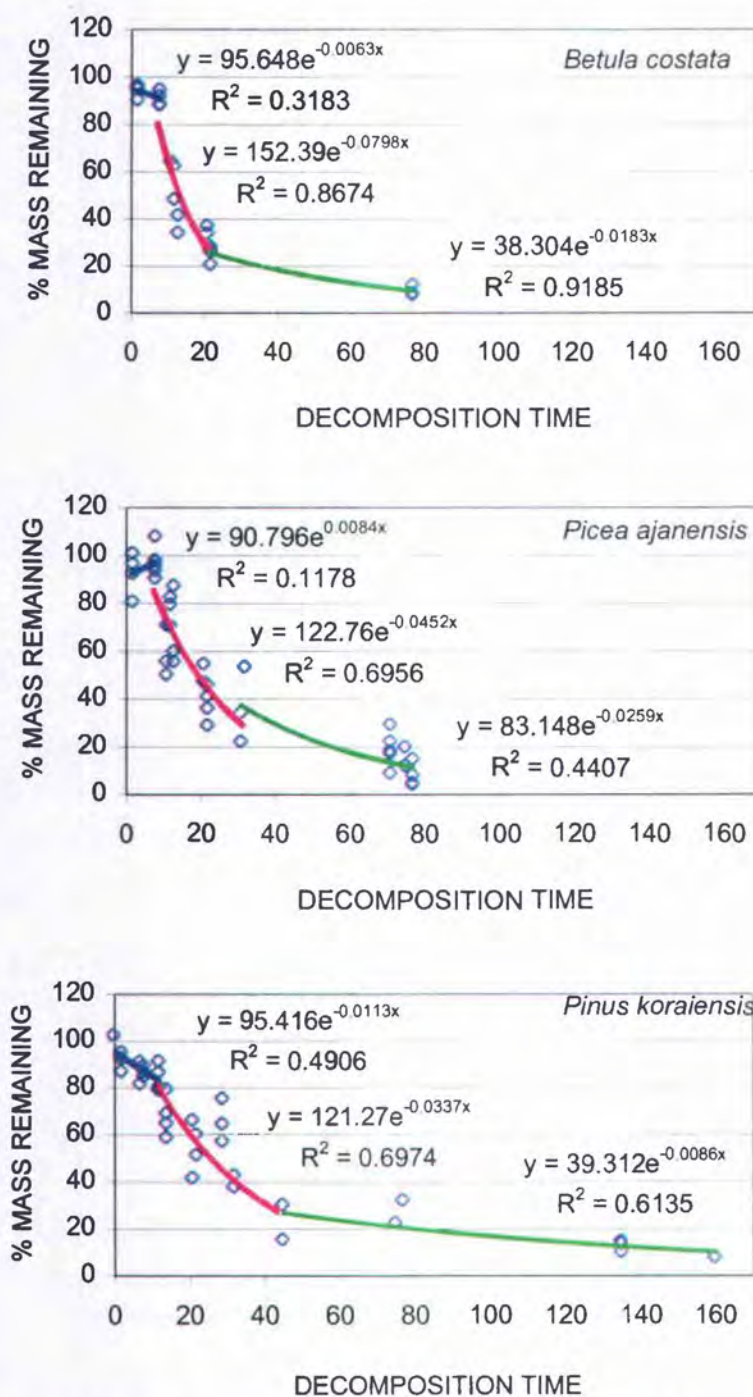


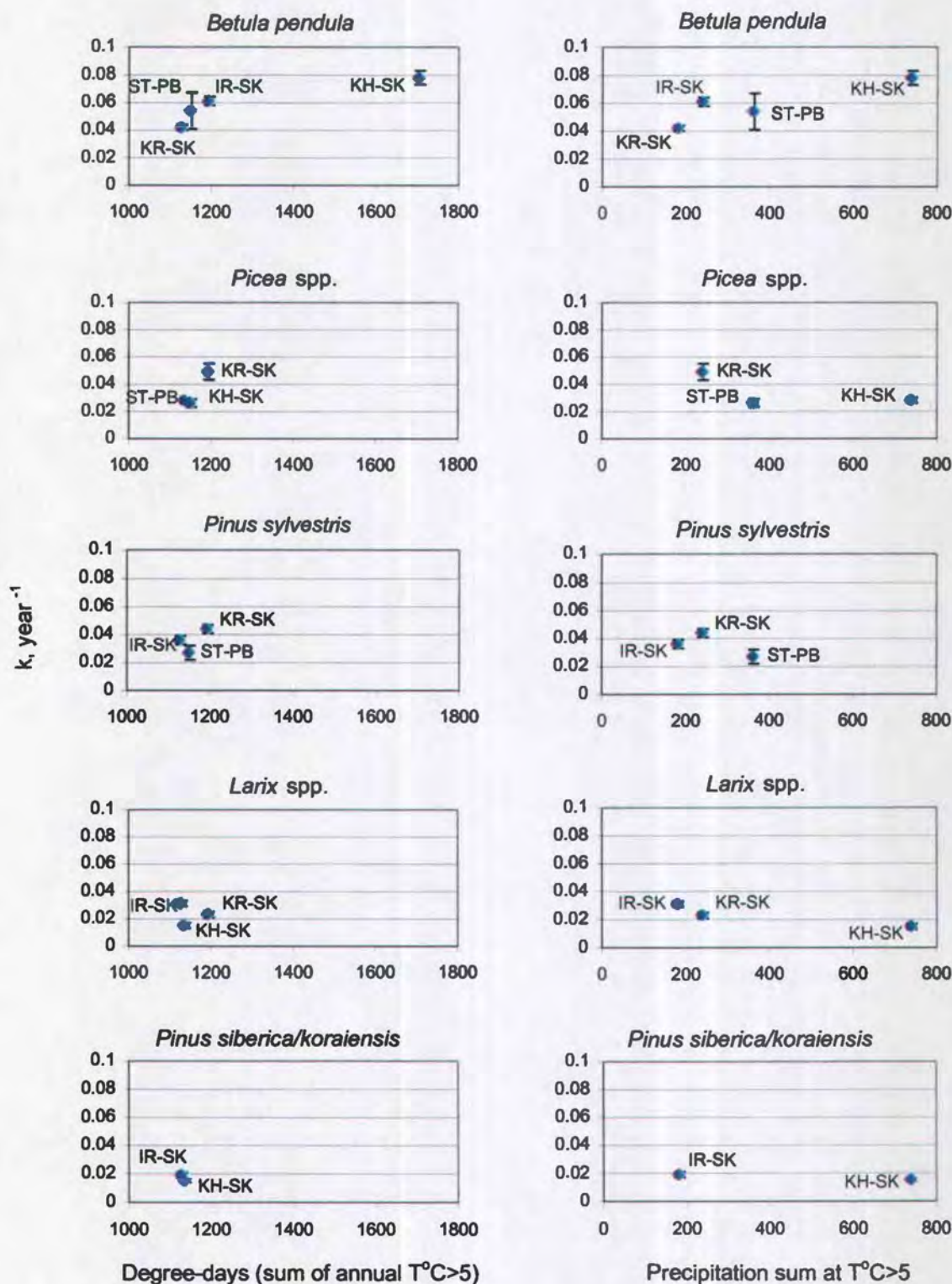
Table 3-15. Coefficients of regression used to estimate decomposition rates in each of three phases for *Betula costata*, *Picea ajanensis*, and *Pinus koraiensis*

Species	Phase of decomposition	Regression coefficients ^a				Adj. R ²
		Y ₀ (%)	k (year ⁻¹)	p-value*	N	
<i>Betula costata</i>	Phase 1	95.65	-0.006 (0.004)	0.1452	8	0.20
	Phase 2	152.39	-0.080 (0.008)	0.0001	16	0.86
	Phase 3	38.30	-0.018 (0.002)	0.0002	8	0.90
<i>Picea ajanensis</i>	Phase 1	90.80	+0.008 (0.008)	0.3317	10	0.0075
	Phase 2	122.76	-0.045 (0.006)	0.0001	24	0.68
	Phase 3	83.15	-0.026 (0.008)	0.0096	14	0.39
<i>Pinus koraiensis</i>	Phase 1	95.42	-0.011 (0.003)	0.0053	14	0.45
	Phase 2	121.27	-0.034 (0.005)	0.0001	19	0.68
	Phase 3	39.31	-0.0086 (0.0028)	0.0215	8	0.55

^a The regression was of the form $Y_t = Y_0 \cdot e^{-kt}$ where Y_t is the percentage of the mass remaining at time t (years), Y_0 is the initial mass in percent dry weight, and k is the decomposition rate constant

* P-value for the comparison of decomposition-rate constants to zero.

Figure 3-16. Decomposition rates of five species plotted against degree-days and sum of precipitation for monthly $T^{\circ}\text{C} > 5$.



3.7 DISCUSSION

3.7.1 Decay classification

The five-class system used to assign logs and snags to decay classes, was consistent in most aspects with that used in other studies (Triska and Cromack 1980, Christensen 1984, Harmon et al. 1987, Storozhenko 1992, Pyle and Brown 1999). However, there were some differences. While the decay class description adopted from Fogel et al. (1973), MacMillan et al. (1977), and Maser et al. (1979) worked well for most coniferous species, it had to be modified for birch, a species that retains its bark through the entire decomposition process. Presence of bark on birch CWD was the most important difference between this species and conifers. Bark retention by birch prevented sapwood and heartwood from sloughing, thus introducing secondary differences between birch and conifers. Aside from bark retention, the other biological and fragmentation indicators of birch were similar to conifers. Not all hardwoods, however, behave like birch (*Betula pendula*). Some lose bark rapidly. Maple and oak in the hardwood forests of Connecticut were found to lose most of their bark by decay class two (Pyle and Brown 1999). Similar conditions were observed in our study for *Betula costata* in the Russian Far East. This species of birch, unlike *Betula pendula*, has thin brittle bark that has a tendency to break at the log surface early in decomposition, thus exposing the inner tissues to similar decomposition process as conifers.

Individual conifer species had minor modifications from the decay classification developed in Pacific Northwest of the U. S. For conifers, the characteristics of the logs associated with decay class one were similar to those used in other studies, including sound bark on the bole (Triska and Cromack 1980), needles, twigs (Harmon et al. 1987), branches, and bark on branches.

Decay class two CWD still had most of its bark on bole (especially *Pinus siberica/koraiensis* and *Larix* spp.), 20 to 55 percent of the sampled logs and snags had twigs present, in 50 cases we recorded the presence of conks, in 35 cases the presence of brown rot, and in 55 cases the occurrence of white rot on the sampled CWD. Also, *Pinus siberica/koraiensis* had a high percentage of CWD pieces with friable and sloughing sapwood. Some of these findings contradict with the decay class two description for *Pseudotsuga menziesii* by Triska and Cromack (1980), who indicated this class had a presence of intact bark, absence of twigs less than 3 cm in diameter as well as no evidence of invading rot. The consistency in both classifications was that bole bark is still present and sapwood is partly soft in decay class two logs.

Decay class three CWD had soft wood as the primary surface substrate due to friable and sloughing sapwood, although, 20 to 85 percent of the logs and snags still had some bark present on boles and that corresponds with the decay class three description of Triska and Cromack (1980). They emphasized, however, the presence of sound heartwood in this class, which can support its own weight and observed invading rot only in the sapwood. In contrast, we encountered friable heartwood (indicating extensive decay) in up to 60 percent of class 3 pieces, although, despite the heartwood decay these pieces were still able to support their own weight. Unlike Storozhenko (1992) who defined decay class three *Picea abies* logs in the Kostroma oblast' of Russia as having complete moss cover, only 40 percent of our decay class three spruce logs had some moss cover.

Decay class four logs in our study were associated with spongy wood as the primary surface substrate due to friable sapwood and heartwood. Bark was detached or absent as reported by Triska and Cromack (1980). The similarity with their system also was the presence of rotten heartwood, which could not support its own weight and the presence of invading roots throughout the log tissues. Some of the logs in this decay

class had an elliptical cross-section as in Harmon et al. (1987), although this characteristic was variable and was found in 30 percent to 85 percent of all sampled logs depending on species. Moss cover was more common as in Storozhenko (1992), which was indicated by the fact that 70 to 95 percent of all logs sampled had this characteristic, although the percent moss cover varied significantly from log to log.

Finally, decay class five logs were associated with the loss of the former log dimensions and the presence of saplings growing on the logs (Storozhenko 1992). Often, we were able to locate logs only by outline on the soil surface, similarly to Storozhenko (1992). Bark on the bole was rarely present with invading rot throughout CWD piece (Triska and Cromack 1980). In most cases, sampled logs were moist and their wood was friable, structure-less and reddish-brown, changing to brown powder when dried (Triska and Cromack 1980). The other important characteristics associated with decay class five were log scattered (cross-section elliptical), log collapsing (unable to support its own weight), log covered with moss, presence of brown rot, and branch stubs moving when present.

One of the characteristics that were associated with coniferous logs of decay classes four and five was case hardening. This condition occurs when outer tissues dry out while inner tissues continue to decompose, thus forming a friable material surrounded by hard shell. Pyle and Brown (1998) suggested that case hardening is most likely occurs on snags of maple and oak that have been standing for a long period. Harmon et al. (1995) indicated that case hardening is typical for logs and snags in seasonally dry tropical forests. In our study, case hardening was associated with decay class three, four, and five of larch, pine, and especially spruce logs which were found in the areas damaged by catastrophic disturbances (windthrow in particular) and were suspended in the air for at least part of the decomposition process. This finding is attributed to the relatively hot, dry

summers that are common for the continental climate of western and eastern Siberia.

The five-decay class system did not completely eliminate the ambiguity associated with borderline logs. The most difficult decision we faced in the field was separating decay classes two and three as well as three and four logs from each other. The same problem has been common in other studies. Pyle and Brown (1998) indicated that 15 percent of the logs assigned to decay classes two and three were not consistent with the calculated decay-class specific density. This inconsistency may be associated with the variability of decay class three, as indicated by the maximum standard deviation of decay-class specific density in decay class three (Figure 3-4). This pattern is related to the nature of the decay class description system. As decay classes one and five are on the ends of decomposition gradient, they are more definite. Decay class one mostly includes recently killed trees with minimal or no indications of decomposition (density or volume loss via fragmentation). Decay class five, on the other hand, includes completely decomposed trees with obvious indications of density and volume loss. The boundaries between decay classes two and three and three and four do not have such clarity, capturing logs that are in the most variable stages of decomposition, where a mixture of biological and fragmentation indicators make it more difficult to assign a specimen to a particular decay class. Thus, these three decay classes have higher variability in density than decay classes one or five. The age distribution of logs by decay classes (Appendix 3) may also support the idea as logs in the middle of the decay class sequence have a larger age range. The greatest mix of "times since tree death" takes place in decay classes two to four with the widest range of "times" falling into decay class three for three species out of six. If decomposition rate is relatively constant, this wide time range would correspond to a wide range of wood densities, thus increasing the variability of the decay class three. These

findings correspond with those of Pyle and Brown (1998) who indicated the decay class three logs are the most variable.

The overlap we observed between adjacent decay classes, indicated by both densities (Table 3-3) and ordination results (Figure 3-6), contradicts the idea that decay class 3 has maximum overlap with other decay classes. The overlap in density is highest in decay classes one and two and decay classes three and four with these pairs being statistically similar. Similarly, the ordination indicates that decay classes one and two as well as four and five occupy the same ordination spaces. Although, decay class three overlaps other decay classes, it occupies a different space in the ordination. Interestingly, Storozhenko (1992) in his five-decay class system for spruce indicates decay class three also being distinct, while decay class two logs were a combination of decay classes one through three, and decay class four logs being a combination of decay classes three and four.

These results may have several interpretations. There may be three distinct conditions of CWD that are more easily detected and differentiated visually, thus making a five-decay class system overly-detailed. In addition, the decay class two logs and snags in our study could have been skewed towards decay class one, while logs of decay class 4 were skewed towards decay class five. Another interpretation may be that the decomposition of logs and snags in decay class two is represented mostly by volume loss via fragmentation (bark, leaves, twigs, and branches loss) and less by wood density loss (the activity of wood deteriorating organisms is in the initiation stage). If true, decay class two log density should not differ from that of decay class one. Decay classes four and five, similarly, do not have tremendous differences in wood density because by that time the wood in both classes is in advanced stages of decay. The differences in bole length or cross-section shape, that could separate decay class four from five, however, are not incorporated into density calculations. To distinguish decay classes, some other characteristics, such as percent of cross-section

occupied by rot, stage and type of decay, or a phase of wood humification (Shorohova and Shorohov 1999) could be used for separation. However, these methods are time consuming and require a large effort, and thus, are unlikely to be used by inventory crews in the field.

There are different patterns in density change with decay class that have been observed. Various sources report a gradual decrease in density with decay class (Triska and Cromack 1980, Shorohova and Shorohov 1999). Harmon et al. (1987) indicated that density of *Abies concolor* decreased gradually, whereas for *Pinus jeffreyi* and *Calocedrus decurrens* it remained fairly constant until decay class four. The latter pattern was also reported by Torres (1994) for logs of *Corilla racemiflora* in tropical forests of Puerto Rico. Hale and Pastor (1998) indicated decrease in mean densities of maple and oak logs in relation to decay class with a small decrease from decay class one to decay class two and a more dramatic decrease from decay class two to decay class four. The decrease in decay-class specific density we observed from decay class one to decay class five was similar to that reported by Hale and Pastor (1998) with exception that we also observed no decrease in density from decay class four to decay class five for most species. Snags of *Larix* spp. (Appendix 5) and *Pinus koraiensis* (Appendix 5) showed a different patterns of decay in our study than other species by maintaining almost constant density until decay class three. In some instances an increase in density of the snags from decay class one to decay class two, similar to that reported by Sanders and Wein (2000) and probably associated with a drying effect, was recorded. All other species showed a similarity in density loss in first two decay classes for logs or snags.

We suggest there are four different patterns in CWD density loss. The first one is exemplified by *Betula pendula* as observed in our study (Table 3-3) with a gradual, almost linear, density decrease from decay class one to decay class five. This gradual decrease is attributed to prolonged

bark presence preventing inner tissues from drying and rapid simultaneous decomposition of sapwood and heartwood associated with the absence of decay-suppressing substances in the heartwood. The second pattern is found in species with decay-resistant heartwood as typified by *Pinus siberica/koraiensis*, *Pinus jeffreyi*, *Larix* spp., *Calocedrus decurrens*, *Corilla racemiflora*, and *Malnikaria* spp. For these species basically no change in density is observed until decay class three or four, as bark and less-resistant sapwood slough off leaving solid, long-lived, decay resistant heartwood. The third pattern we associate with such species as *Pinus sylvestris*, *Picea* spp., and *Pseudotsuga menziesii*, where the heartwood is not very resistant or the sapwood to heartwood ratio is very high even for mature trees. In this case, bark sloughs off and decomposition starts from outside with sapwood and then the heartwood slowly deteriorating. Finally, the fourth pattern is associated with species susceptible to heart rot similar to oak and maple studied by Hale and Pastor (1998) in Minnesota. CWD decomposition in this case is complex as the decay of log or snag proceeds simultaneously from the inside out as well as from the outside in.

3.7.2 Decomposition rate-constants

It has been emphasized that a single exponential curve (Olson 1963) does not always perfectly describe the CWD decomposition process (Hale and Pastor 1998; Harmon et al. 2000, Sanders and Wein 2000). Many species decompose slowly at first due to the high moisture content, decay-resistant heartwood or the long time required for decomposer organisms to become established (Grier 1978, Harmon et al. 2000). A phase of slow decomposition (Hale and Pastor 1998, Harmon et al. 2000), often modeled as a time lag (Grier 1978, Naesset 1999, Harmon et al. 1995), is associated with a regression intercept above 100, while an intercept below 100 indicates a rapid decomposition rate at the beginning of the decomposition

process (Harmon et al. 1990, Harmon et al. 1995). Our study also indicates that mass loss for some species does not decrease exponentially. For example, logs of *Betula costata*, *Picea ajanensis*, and *Pinus koraiensis* (Figure 3-14) appear to go through three stages of decomposition. Birch seems to have a low decomposition rate for the first 8 years, followed by fast rate for about 16 years, and then a slow decomposition rate for the remaining 55 years. Spruce and Korean pine appear to go through a period of slow decomposition for the first 8 and 12 years (respectively), followed by a fast rate for 16 years for spruce and 33 years for pine, and finally reaching an extended period of slow decomposition for the duration of at least 45 years for spruce and 115 for pine.

To account for these changes occurring over the course of decomposition, one can break down the process into more uniform periods. Hale and Pastor (1998), for example, calculate decomposition by decay classes. This approach resulted in moderately slow decomposition rates for decay class 1 logs, slow - for decay class 2, increased rate for decay class 3 and an even higher rate for decay class 4 logs. Harmon et al. (2000) used a decomposition vector approach estimating woody detritus decomposition dynamics for a range of decay classes by re-sampling decomposition rates over 3-year intervals. This approach suggested three distinct phases in log decomposition: slow - when colonization by decomposers occurred, fast - a period of rapid mass loss, and slow - when mass losses are minor. We also tried to determine the decomposition rates for each of three phases of birch, spruce, and Korean pine decomposition by fitting an exponential curve through the mass loss data associated with each phase (Figure 3-15). This indicated a decomposition rate of -0.0063 , $+0.0084$, and -0.011 for the first phase, -0.080 , -0.045 , and -0.034 for the second phase, and -0.018 , -0.026 , and -0.0086 for the third phase for birch, spruce, and Korean pine decomposition, respectively. A low decomposition rate of spruce in the first phase is associated with the fact

that most of the logs in this phase were collected in stands damaged by some sort of catastrophic event (windthrow or insect outbreak), thus enhancing the drying effect in the open sun. Such conditions could influence the rate of decomposition and increase the density via a shrinkage effect. The relatively high decomposition rate of Korean pine logs in the first phase can be explained by a high rate of fragmentation (bark and sapwood loss) occurring in this species. The low decomposition rate of pine observed in the third phase could be associated with the decay-resistant and thus slow-decomposing heartwood.

Fragmentation is a source of concern for determining correct decomposition rates. Lambert et al. (1980) pointed out that fragmentation is probably the most serious source of error for estimating change in wood mass with time. Graham and Cromack (1982) and Harmon and Chen (1991) indicated that about 30% of the mass of CWD from logs is lost via fragmentation, thus fragmentation losses from the bole should be considered for the calculation of decomposition rates. Christensen (1984) found that the significance of physical weight loss in oak increases at a relative wood density of 0.30-0.35 g/cm³, when wood friability reaches the stage that any slight mechanical disturbance or activity may cause the fragmentation of the wood material. If volume losses are not incorporated into decomposition rate calculations, the decomposition curve forms an asymptote (Harmon et al. 2000), whereas with volume loss included the curve appears to have a slight but steady decline, which was observed in our study as well.

The decomposition rates determined in this study were species dependent and within the range determined by other researchers for Russia, Norway, and northern China (Table 3-16). Birch (*Betula pendula*) had the highest decomposition rate among all species in all these studies, which is probably explained by the lack of decay resistant heartwood in this species and presence of bark on the bole, which keeps moisture trapped

Table 3-16. Comparison of decomposition rates determined in this study with decomposition rates obtained by other researchers in the same regions of study

Species	Region	Study	k, year ⁻¹
<i>Betula pendula</i>	St.-Petersburg	This study ^a	-0.054 (0.013)
		Shorohova 2000 ^b	-0.058
		Harmon et al. 2000 ^a	-0.046
		Tarasov 1999 ^b	-0.026 to -0.051*
		Krankina & Harmon 1995 ^a	-0.045
<i>Picea abies</i>	St.-Petersburg	This study ^a	-0.026 (0.003)
		Shorohova 2000 ^b	-0.031
		Harmon et al. 2000 ^a	-0.033
		Tarasov 1999 ^b	-0.019 to -0.033*
		Krankina & Harmon 1995 ^a	-0.034
	SE Norway	Naesset 1999 ^b	-0.028 to -0.041**
<i>Pinus sylvestris</i>	St.-Petersburg	This study ^a	-0.027 (0.005)
		Harmon et al. 2000 ^a	-0.035
		Tarasov 1999 ^b	-0.014 to -0.023*
		Krankina & Harmon 1995 ^a	-0.033
	Krasnoyarsk	This study ^a	-0.044 (0.003)
	Tomsk	Wirth et al. 2000 ^c	-0.034
<i>Pinus koraiensis</i>	Khabarovsk	This study ^a	-0.015 (0.001)
	Changbai, China	Harmon & Chen 1991 ^b	-0.016
	Changbai, China	Harmon & Chen 1991 ^c	-0.023

^a The decomposition rate was determined based on percent mass loss

^b The decomposition rate was determined based on percent density loss

^c The decomposition rate was determined based on input-to-biomass ratio

* The decomposition rate range is associated with diameter range of 10 to 50 cm

** The decomposition rate range is associated with diameter range of <10 to >25 cm

inside. Birch snags stripped of bark have been known to decompose much slower than those with bark remaining (Chen 1998, personal communication). Korean pine (*Pinus koraiensis*) was the slowest decomposing species studied and this is attributed to the decay resistant heartwood as well as to the large size of the trees we sampled. White pines and larch were the most decay resistant species among those we sampled. Their large size (Appendix 3) might be one of the major factors reducing decomposition, as large diameter is often associated with low surface area to volume ratio, which prolongs the colonization process by wood-destroying organisms, and reduces the sapwood-to-heartwood ratio. Previous work in Russian forests indicates that the decomposition rate is negatively correlated with the size of CWD (Tarasov, 1999). Although it is true that white pines and larch had the largest logs and snags sampled, the presence of decay-resistant heartwood is considered the main reason for the low decomposition rates of these species. Historically, the local people recognized the decay resistance of white pine and larch, giving these species preference in house construction. Although, decomposition processes differ for logs and snags in natural environments and for those in structures, it has been known that houses built of *Pinus siberica* logs to last over 200 years (Ogniov 1997, personal communication), and those constructed of *Larix siberica* – well over 100 years (Kakorin 1998, personal communication).

The other species had decomposition rates within the range of those of birch and Korean pine. Alban and Pastor (1993) found a significant effect of species on the decomposition rate with quaking aspen (*Populus tremuloides* Michx.), white spruce (*Picea glauca* (Moench) Voss), red pine (*Pinus resinosa* Ait.), and jack pine (*Pinus banksiana* Lamb.) listed in descending order of decomposition rates. The differences in conifers and birch underline the differences in decomposition process of these species. While decomposition in conifers is a combination of density loss and mass

loss via fragmentation, in birch this process is primarily due to density loss because bark, which is retained on birch boles through the entire CWD life often prevents sloughing (i.e., fragmentation). As decomposition rates of larch and white pines are lower than of any other sampled species, the idea that a significant presence of larch and Siberian and Korean pines in the eastern regions and lower decomposition rates of these species may contribute to higher CWD stores in the eastern regions of Russia (Krankina et al. in review) is supported.

The differences in decomposition rates between logs and snags observed in our study correspond with the results of other researchers. Onega and Eickmeier (1991) indicated that the decomposition rate of logs was higher than the rate of snags of *Acer saccharum* in Tennessee. In our study the snags of coniferous species in general had lower decomposition rates than logs of the same species. There might be two explanations for this phenomenon. First, the decomposition time range of the sampled snags is narrower than that of the logs (Table 3-13). In twelve cases out of sixteen the maximum decomposition time of snags is below 20 years. For coniferous snags this is too short a time to show significant losses in density or volume. During this period, the volume loss is small (branches, bark, some sapwood), while the density loss is low (and density can even increase due to wood drying effects). In addition, sloughing of less dense and more decayed tissues can result in a minimal overall density change. Due to insufficient moisture because of increased drying of snags, their decomposition may be slower than that of logs. In contrast, moisture in logs is higher because they are often under the canopy, thus affected less by drying. Their proximity to the soil possibly insures quicker fungal and insect invasion, thus quicker deterioration of woody tissues. Deteriorated tissues can store higher amounts of water than fresh woody tissues due to a higher maximum water capacity. Compared to conifers, birch logs and snags had similar decomposition rates. Here, bark retention creates

analogous moisture conditions within the log and snag tissues, thus leading to similar decomposition rates.

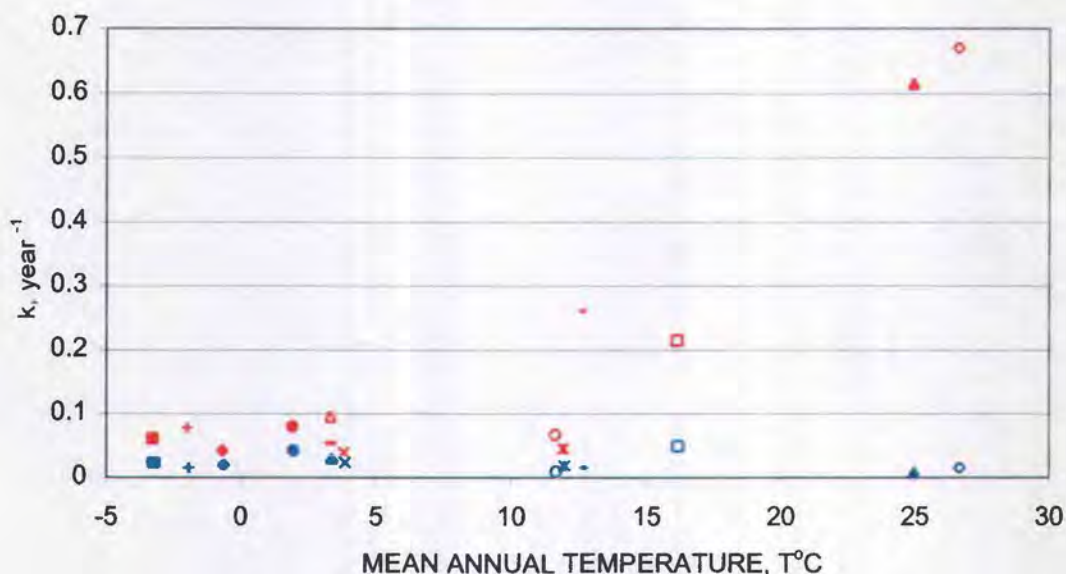
Moisture has been observed to have a profound non-linear effect on decomposition in the laboratory studies (Chen 1999, Hicks 2000). At low levels of moisture the decomposition rate is low. When moisture increases to the point of saturation or water logging, most of the decomposers are unable to function due to a lack of oxygen. Field measurements suggest that moisture is important in some ecosystems. For example, Harmon et al. (1987) found an inverse relationship between decomposition rate and annual precipitation for conifer boles in the western U. S. This is consistent with laboratory studies that indicate excess moisture reduces aeration (Harmon and Chen, 1991). At the same time, Marra and Edmonds (1996) implied that excess moisture did not seem to control seasonal variations of decomposition in the field.

Temperature appears to be a more important factor determining decomposition rate-constants than moisture (Marra and Edmonds 1996). Temperatures approaching the freezing point, for example, arrest fungal growth and bacterial activity, although are unable to eliminate decay completely. There is also an indication that the activity of fungi approximately doubles for every 10°C rise in temperature (Q_{10} factor) (Panshin and de Zoew 1970, Chen 1999, Hicks 2000). Laboratory analysis of the relationship between decomposition rate and temperature performed in the controlled environment indicated an increase in decomposition rate with the temperature, followed by a sharp drop in decomposition rate once the temperature reaches an optimum value of approximately 40°C (Chen 1999, Hicks 2000). Our study, however, did not find any of the above-mentioned relationships between decay rate and climatic conditions. The lack of any differential effect of temperature or precipitation on decomposition rates observed in our study may be explained by the fact that the data were collected over a narrow range of conditions (Appendix 1).

All the sites were located in the southern taiga zone, and thus, differences in temperature and precipitation are likely too small to have differential effects on decomposition rates. This hypothesis is supported by the statistical analysis (stepwise regression), which indicated that region (which may include some aspects of temperature and precipitation differences) explained only 0.5% of the variation in percent mass remaining. At the same time, decomposition time, position, and species had a much more profound effect on percent mass remaining. The other possibility is that the method of decomposition rate determination is too rough and the effects of temperature and moisture are too minor to have an effect along the temperature gradient. The other possibility may be that our chosen measures of temperature and moisture are not appropriate for the type of analysis we are trying to perform.

At the global level, Chambers et al. (2000) found a high correlation between decay rates and mean annual temperatures. A compilation of world decomposition rate data including those from our study suggests that while there is no significant effect of temperature on wood decomposition for decay-resistant species, there is a temperature effect on decay-susceptible species (Figure 3-17). The decomposition rate of decay-susceptible species appears to increase exponentially as the mean annual temperature increases. At the same time these data suggest that it is difficult to find any effect of temperature on decomposition unless the mean annual temperatures in the regions of study exceeds 13°C.

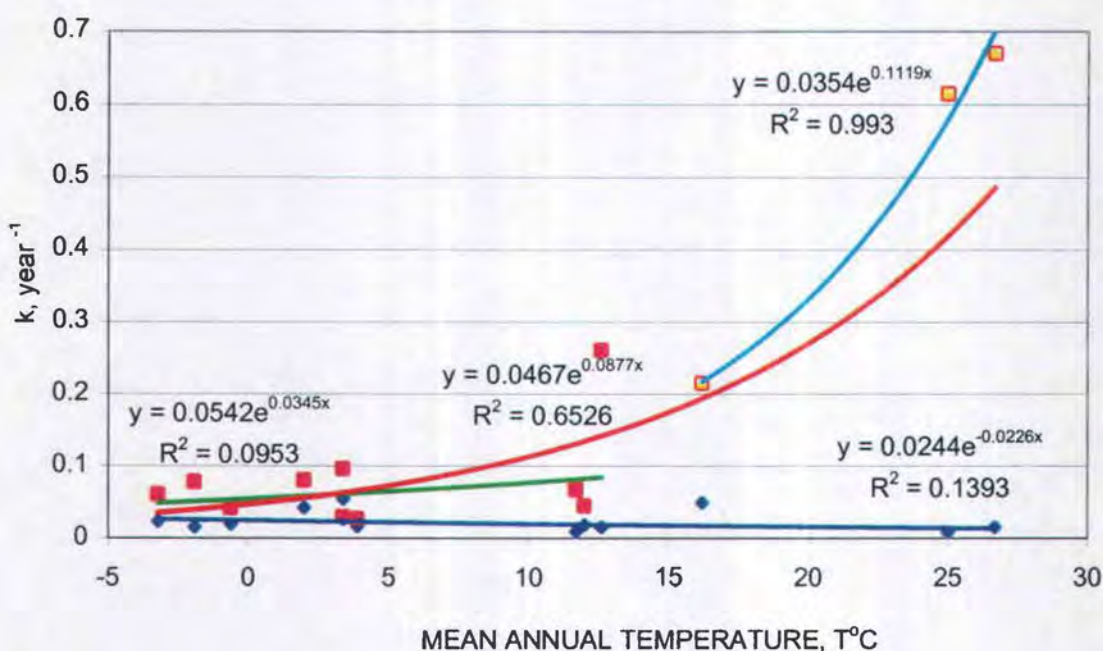
Figure 3-17. Decomposition rates obtained from different regions of the globe plotted against corresponding mean annual temperatures.



LEGEND:

- *Betula pendula*, Krasnoyarsk region (this study)
- *Larix siberica*, Krasnoyarsk region (this study)
- + *Betula pendula*, Khabarovsk region (this study)
- + *Pinus koraiensis*, Khabarovsk region (this study)
- ◆ *Betula pendula*, Irkutsk region (this study)
- ◆ *Pinus siberica*, Irkutsk region (this study)
- *Populus tremuloides*, North-Central Minnesota (Alban and Pastor, 1993)
- *Pinus banksiana*, North-Central Minnesota (Alban and Pastor, 1993)
- △ Hardwoods (maple, ash, birch, beech), New Hampshire (Arthur et al. 1993)
- △ *Abies balsamea*, New Hampshire (Lambert et al. 1980)
- *Betula pendula*, St.-Petersburg (this study)
- *Picea abies*, St.-Petersburg (this study)
- Hardwood spp., Western Oregon (Turner et al. 1995)
- *Thuja plicata*, Western Oregon and Washington (Sollins et al. 1987)
- × *Tilia amurensis*, China (Harmon and Chen, 1991)
- × *Pinus koraiensis*, China (Harmon and Chen, 1991)
- * *Acer* spp., Indiana (MacMillan 1988)
- * *Quercus* spp., Indiana (MacMillan 1988)
- *Diospyros virginia*, North Carolina (Mattson et al. 1987)
- *Robinia pseudoacacia*, North Carolina (Mattson et al. 1987)
- *Eucalyptus calophylla*, Western Australia (Brown et al. 1996)
- *Pinus pinaster*, Western Australia (Brown et al. 1996)
- ▲ *Bursera simaruba*, Mexico (Harmon et al. 1995)
- ▲ *Manilkara zapota*, Mexico (Harmon et al. 1995)
- ◇ Fast decomposing spp., Central Amazon (Chambers et al. 2000)
- ◇ Slow decomposing spp., Central Amazon (Chambers et al. 2000)

Figure 3-18. Decomposition as a function of mean annual temperatures



- Legend:
- exponent (slow decomposing species)
 - exponent (fast decomposing species combined)
 - exponent (fast decomposing species for T °C range -5 to +15)
 - exponent (fast decomposing species for T °C above 15)

The global level data indicate an increase of decomposition rate with temperature for decay-susceptible species, although, without the optimum observed in the lab (Figure 3-18). For the decay-resistant species, however, we did not find a similar relationship between decomposition rate and temperature. The Q_{10} factor indicating increase in biological activity with temperature increase by 10°C was 0.8 for the decay-resistant species indicating substrate quality may be limiting temperature response for this group of species. The Q_{10} factor calculated for non-decay resistant species was 2.40 and corresponded with value of 2.4 obtained by Chambers et al.

(2000). The curve describing the relationship for the latter species may be broken into two parts, a minor response for temperatures ranging between -5 and $+15^{\circ}\text{C}$ and a dramatic increase for temperatures above 15°C . If a Q_{10} is calculated for each part, we get 1.41 and 3.06 for temperatures below 15°C and those above 15°C , respectively. These Q_{10} numbers indicate little effect of temperature on the decomposition rates in cold and moderately cold climates, but a significant increase of decomposition rates as one moves into tropical and subtropical climates. The cause of such increase in decomposition is yet to be determined, but we hypothesize this occurs as a result of insect activities (termites in particular) or other arthropod or faunal "comminuators" that are absent in colder climates.

3.8 CONCLUSIONS

Given the rate that CO_2 concentration has increased in the atmosphere in the last century and the associated increase of global temperatures, management of the global carbon cycle has become essential. Improving management of this cycle depends on better understanding of carbon sources and sinks to the atmosphere. With better knowledge of the processes controlling global carbon budget we may be able to start identifying management scenarios that can help manipulate the carbon cycle to our advantage. The first step towards making valid management decisions in future carbon cycle management is to identify existing carbon pools, their sizes, and the way they contribute to currently observed changes in climate. Coarse woody debris is one such pool within world's forest ecosystems. Given its size and the fairly long residence of carbon in this pool, more information is required to gain complete understanding about the CWD role in carbon cycling and review our options in managing this pool to store more carbon.

This project involved analysis of data collected over a four-year period with the purpose of determining CWD stores and dynamics in the boreal forests of Russia. Specifically, the effects of CWD state of decay, species, position, and geographic location on these dynamics were examined. The species studied showed diverse decomposition patterns, with birch and conifers having different characteristics to indicate decay classes. The most significant differences in decay class specific density were associated with decay classes and species, making regional and positional differences of lesser concern for CWD inventories. The decay-class specific density differences among species declined with decay class indicating that species identification of CWD in advanced stages of decomposition is of minor importance in CWD stores inventories.

The order of increasing woody debris decomposition rate-constants (k) among the studied species was birch > spruce > Scots pine > larch > white pine. The fast decomposition of birch may be associated with the lack of decay-resistant heartwood and presence of bark during the entire decomposition process of this species. The slow decomposition of white pine may be associated with the presence of decay-suppressing substances in its heartwood, and its large size, which is closely related to a low surface area to volume ratio and to a low sapwood-to-heartwood ratio. Differences in decomposition rates of logs and snags indicated that disturbances creating snags increase overall turnover time of CWD pieces for conifers, possibly by means of decreasing decomposition through excessive drying.

No effect of the climatic conditions on decomposition rates of the species studied was found among the Russian sites. Examination of the effect of temperature on decomposition rates at the global level of the most decay resistant and decay susceptible species suggests that while there is no or little correlation between mean annual temperature and decomposition rates of decay-resistant species, there is a positive

correlation between temperature and decay-susceptible species which appears once a mean annual temperature of 15°C is reached.

The results of this study suggest that the carbon sequestration potential of Russian forests may be increased through changes in species composition. While a faster tree growth rate is associated with higher sequestration rate of carbon, slower CWD decomposition rate prolongs the residence time of carbon in CWD. Therefore, by manipulating the species composition in managed forests we can increase the carbon sequestration potential of an ecosystem. Also, there was some indication that rotation age may increase carbon sequestration potential as larger trees store more C, but when they die have a tendency to decompose slower than smaller diameter trees of the same species. CWD position may also be one of the characteristics that can be used to increase carbon sequestration potential as snags in general have slower decomposition rates than logs.

This study examined the CWD decomposition dynamics with the intent to help understand the role of boreal forests in the carbon budget within a framework of global forest ecosystems. The conclusions made here may have an important impact on the forest management for carbon sequestration in the boreal forests of Russia as this part of the world has a great capability to increase its carbon sequestration potential with changes in silviculture systems, fire management, and timber harvest practices.

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CHAPTER 4

MANAGEMENT IMPLICATIONS

Given that CO₂ concentrations continue to rise in the atmosphere and that detectable changes in climate have been associated with past increases in CO₂, a strategy to mitigate these changes is developing. Three types of actions have been proposed: 1) adapt to climate change; 2) take direct action to reduce atmospheric inputs of CO₂, and 3) take indirect steps that will stabilize or reduce atmospheric concentrations of CO₂. In this chapter I discuss all three types of actions and then evaluate the degree that results from my study can be used in the third kind.

Adaptation to climatic changes is one way to deal with global warming. Adaptation techniques may include engineering of structures and technologies, adapting plants for hotter environments, or simply moving to a more favorable environment. Engineering structures could prevent bank erosion on ocean shores associated with increasing sea level or concentrate on construction of new structures on high grounds. For areas threatened not by high sea level but by high daily temperatures, advanced air conditioning technology may be developed. Genetic engineering could be used to creating plants that can survive and produce crops under warmer and possibly drier conditions. Traditional planting zones for species could be moved. For example, forests could be relocated by distributing seeds of tree species in what is now tundra, thus promoting faster intrusion of forests into tundra regions as permafrost retreats further northward. For some locations, however, the only solution will be to move entire economies and societies. For example, Pacific islands that originated on coral reefs and atolls may be completely covered with water as global sea level

increases. Thus, the population from such places will be forced to leave their homeland. Unfortunately, our lack of knowledge about the rates at which increases in global temperature and rise of oceans will occur, raise questions as to the extent these adaptation techniques will succeed.

Direct action includes decreasing use of fossil fuel as a source of energy by either finding some other energy sources and/or increasing energy conservation. Both of these actions would have major impacts, but are very difficult to implement for a variety of reasons. There is a lack of willingness to cut fossil fuels use because there has been little perceived effect of climate change for most regions and countries. This coupled with inconclusive predictions on the effect of climate change and the ever-growing demands for the energy caused by population and infrastructure growth means that the perceived benefits are low compared to the cost. There is also a resistance in developed countries to reduce fossil fuels because they are currently a significant source of energy (60% of all energy in the U. S. alone) and have a low cost. For developing countries there is a resistance to a global decision of reducing fossil fuels use, because the developed countries built their economy with cheap fossil fuels. Even if there was the political and social will power to reduce fossil fuel use, the lack of a clean, cheap, and sufficient energy substitute for fossil fuels imposes limitations. For example, hydropower has environmental costs given that it floods large land areas, removes wetland habitats, threatens the extinction of anadromous fish, decreases land productivity, and causes the destruction of deltas. Nuclear power, once viewed as a viable alternative to fossil fuels, has high costs, lacks recycling and storage technology for radioactive byproducts, and is perceived to have a significant risk of devastating accidents. Wind and solar power are maintenance-expensive, of insufficient capacity, too localized and weather dependant. Bio-energy is currently produced in very small quantities relative to the need for energy.

Given these difficulties of adapting to and directly approaching global warming, alternative, indirect ways to decrease the impact on global climate change have recently gained more attention. Indirect steps include actions associated with managing the ecosystems so that they store larger quantities of C and thus reduce or stabilize atmospheric CO₂. With certain management techniques the world's forest ecosystems may serve a key role in this strategy. Since only 10% of the world's forests are estimated to be actively managed (WRI 1990), there may be potential for improving carbon sequestration. Carbon stores in forest ecosystems are closely related to overall ecosystem dynamics and depend on disturbance type and regime, successional dynamics, tree growth and mortality rates, and rates of decomposition. Manipulation of these processes by forest management may increase the ability of forest ecosystems to sequester carbon. Management techniques that can enhance forest ecosystem's carbon sequestration and storage potential include fire control, creation of plantations on degraded forest and agricultural lands, and silvicultural treatments that increase productivity, rotation length, and detritus stores. In the following paragraphs I examine the impact of these various indirect steps for Russia and compare this to the overall stores and flux of carbon associated with Russian forests.

Globally forests contain 1146 Pg C in vegetation and soils (IPCC 2000). Almost half (559 Pg C) of that is stored in boreal forests of the world with 88 Pg C in live biomass (IPCC 2000). Russian forests account for over 20% of the world's forest area and about 50% of all boreal forests (Krankina et al. 1996), and according to various sources store 29.5 – 50.4 Pg C in live biomass, 72.5 – 214.4 Pg C in soils, 54 – 138 Pg C in peat, and 26 – 31.4 Pg C in detritus with net C accumulation in all pools of 0.06 to 0.49 Pg C (Table 4-1). Whether Russian forests serve as carbon sink or source is still uncertain. Various literature sources used different calculation methods

and estimated Russia as a sink of 0.1 - 1.02 Pg C yr⁻¹ or as a source of 0.037 – 0.199 Pg C yr⁻¹ (Shvidenko et al. 1996).

The approximate impact of various management options was assessed by Krankina et al. (1996) (Table 4-2). Fire is a major source of disturbance and tree mortality in boreal ecosystems. In the two-year period between 1989 and 1990, the area damaged by fire in Russia was reported to be at least 3.6 million ha (Dixon and Krankina 1993). Fire control can be improved with controlled burning or some other means to decrease the fuel load in stands. Since over 90% of fires have an anthropogenic origin, simple precautions employed during recreation, fishing, hunting or other activities associated with forests, may reduce fire damage to a minimum. An advanced system of fire search, rapid fire allocation and control may also contribute to lower proportion of forests damaged by fires. A decrease in stand replacing fires by 50% across Russia would have the potential to store an additional 0.48 Pg of carbon in Russian forests (Table 4-2).

Table 4-1. Estimates of C stores, net C accumulation, and annual C flux in Russian forests

Type of C pool	Range in C store/flux
Live biomass*	29.5 – 50.4 Pg C
Soils*	72.5 – 214.4 Pg C
Peat*	54 – 138 Pg C
Detritus*	26 – 31.4 Pg C
Net accumulation in all pools*	0.06 – 0.49 Pg C
Annual C flux to/from Russia**	sink: 0.1 – 1.02 Pg C yr ⁻¹ source: 0.037 – 0.199 Pg C yr ⁻¹

* after Krankina et al. 1996

** after Shvidenko et al. 1996

Table 4-2. Management options to increase C sequestration potential of Russian forests (after Krankina et al. 1996)

Management options	C sequestration potential (Pg C)
Plantations on forest and agricultural lands	0.70
Reduction of stand replacement fires by 50%	0.48
Harvest reduction/increased rotation age	0.42
Increasing stand productivity with silvicultural treatments	0.35
Plantations on sands, drained peat bogs, and mine tailings	0.07
Total of all options	2.02

Establishment of plantations on poorly stocked forest and agricultural lands may also increase carbon storage in Russian forests. Most of Russian forestlands are left to naturally regenerate after being cut. For areas with favorable environmental conditions, the close proximity of seed sources of desirable species, and a high rate of seedling survival, such a forest management system does not create a problem. For less favorable areas, however, it may take over 300 years for the desired species to occupy cutover areas. In the worst cases, cutover areas never regenerate as many become inundated with water and develop into bogs. Vast agricultural lands in Russia, that have been abandoned due to the last two decades of economic perturbations, represent a great potential for increasing carbon stores in forests. Their high productivity, proximity to populated areas, and developed infrastructure mean easy access and limited preparation to become forest plantations. These factors should allow for fairly quick recruitment of these lands into forest production with the purpose of managing the global carbon balance. Planting forests on forest and agricultural lands has the potential to increase the carbon store of Russian forests by 0.7 Pg (Table 4-2). Russian forests can sequester an

additional 0.07 Pg if plantations are established on sands, drained peat bogs, and mine tailings (Table 4-2).

Silvicultural treatments may include measures towards increasing stand productivity, control of input into CWD pool, control of species composition, increase of rotation age, reducing harvest, and to some extent control of CWD position. As higher tree growth rates are associated with higher rates of carbon uptake from the atmosphere, management techniques that improve stand productivity and lead to enhanced tree growth, can increase a stand's carbon sequestration potential. These techniques may include fertilization (which can also indirectly release CO₂ in the form of fossil fuels), planting N-fixing species (alder), draining swampy areas (in some cases), and leaving more plant material during harvesting operations to decompose and enrich soils with nutrients. Increasing stand productivity with silvicultural treatments has the potential of storing additional 0.35 Pg C in Russian forests (Table 4-2).

Manipulating species composition may affect the carbon sequestration and storage potentials of a stand significantly. Fast growing tree species have a tendency to accumulate carbon faster than slow growing ones. At the same time, fast decomposing species release carbon to the atmosphere at higher rates than slow decomposing species. Thus, increasing the proportion of fast growing, slow decomposing species in a stand has an ability to increase carbon sequestration and storage potentials of a stand.

Changing species in Russia could have a large potential impact on the flux and storage of C in CWD (Table 4-3). The current annual carbon flux from the CWD in forest ecosystems from the 763,502,000 ha of Russian land, is estimated to be 0.107 Pg C yr⁻¹ from a store of 3.79 Pg C. An additional flux of 0.015 Pg C yr⁻¹ is also estimated from 38,808,200 ha (Drozhalov et al. 1990), which include forest areas killed by fire and other

Table 4-3. Carbon stores and fluxes of CWD in Russian forests

	C stores (Pg C)	C fluxes (Pg C yr ⁻¹)
Forest land	3.79 ^a	-0.107 ^{aa}
Burns, clearcuts, young plantations, other damaged land	0.52 ^b	-0.015 ^{bb}
Total all land categories	4.31 ^c	-0.122 ^{cc}
Emissions from Russia	N/A	-0.4 ^d
All birch scenario	1.56 ^e	N/A
All Korean pine scenario	8.11 ^f	N/A

^a sum of regional C stores (Ural, Western Siberia, Eastern Siberia, and the Russian Far East) calculated as a product of regional forest-covered area and regional CWD stores per ha (Krankina et al., in review) divided by two.

^{aa} sum of regional C-fluxes calculated as a product of regional C stores by species and species decomposition rates. C stores by species are a product of species covered area (VNIIC 1995) and regional CWD stores per ha (Krankina et al., in review) divided by two.

^b product of area under burns, clearcuts, young plantations and other damaged forest land and corresponding CWD stores (Krankina et al., in review) divided by two.

^{bb} product of C store and mean decomposition rate determined as a ratio of C-flux from forest covered land (^{aa}) to corresponding C store (^a).

^c sum of C stores on forest (^a) and damaged (^b) lands.

^{cc} sum of C fluxes from forest (^{aa}) and damaged (^{bb}) lands.

^d after Flavin 1999.

^e product of total C store (^c) and birch decomposition rate constant of 0.078 yr⁻¹.

^f product of total C store (^c) and Korean pine decomposition rate constant of 0.015 yr⁻¹.

disturbances, clearcuts, and young plantations, thus bringing total C flux from CWD to 0.122 Pg C yr⁻¹. This amount is 30% of 0.4 Pg C yr⁻¹ Russia emitted during 1998 (Table 4-3). The carbon store of CWD including all forest covered land and land under forest killed by disturbances is 4.31 Pg C (Table 4-3). This number is approximately 10% of C stored in live biomass of Russian forests (Table 4-1). It is also almost 7 times smaller than C stores in CWD reported by various sources in Krankina et al. (1996). If all tree species across Russia were changed to birch, the species having the highest decomposition rate among those sampled, and the input

remained constant, C store would decrease to 1.56 Pg C. In contrast, if all tree species were changed to Korean pine, the species with the lowest decomposition rate observed, C store would increase to 8.11 Pg C. The 3.8 Pg C that potentially could be stored in Russian forests under the second tree species change management option, represent a great carbon sequestration potential when compared with carbon sequestration potential of 2.02 Pg C associated with all other management options described in Krankina et al. (1996) (Table 4-2).

Increasing rotation age may also have a significant effect on the ecosystem potential to sequester and store carbon. First, larger trees store more carbon in their tissues than smaller ones. Second, large diameter logs have a smaller surface area and smaller sapwood to heartwood ratio compared to small logs. Because heartwood is often associated with a presence of decay-inhibiting compounds, larger trees generally have lower decomposition rates than smaller ones. Finally, larger trees tend to result in more material left after harvest in the form of coarse roots, tops, and stumps, which can increase detritus stores of C. Reducing harvest as well as changing from clearcut to partial harvest may also increase carbon sequestration. Although, a young forest planted after clearcut has a higher growth rate, the amount of C sequestered by an area covered with young forest is much lower than this amount of C sequestered by the same area covered with mature forest. The combination of harvest reduction and increased rotation length has the potential to add 0.42 Pg of carbon to Russian forests (Table 4-2). Altering the position of CWD, although, not applicable to every forest ecosystem, may contribute significantly to increasing time of C residence in CWD. Our results indicate that decomposition in conifer snags is a much slower process than that in conifer logs. Therefore, creating more snags in a stand may prolong the residence of CWD and thus C residence in the stand.

Although, forest management is not a direct approach to solving the problem of global warming, and more straightforward actions such as reducing fossil fuels use need to be taken, recent analyses indicate that global forests may increase their C absorption and storage under certain management regimes. It has been estimated that Russian forests can increase their current carbon storage by 2.02 Pg on a sustainable basis (Table 4-2). This value is conservative in that it does not include carbon accumulation in soils and forest products. There also appears to be significant potential in manipulating the CWD pool. My preliminary calculations indicate that by changing species, the store of C in Russia could be increased by as much as 3.8 Pg C (Table 4-3). Although, these management changes have limitations due to biological as well as anthropogenic factors, this number is still clearly significant when compared to the other possible management actions related to forests. Therefore, the positive effect of forest management with the purpose of carbon mitigation is difficult to ignore. Moreover, all the management approaches described above may provide additional economic and environmental benefits by increasing forest area and the quality and quantity of timber.

CHAPTER 5

SUMMARY

1. The global carbon cycle is still not fully understood with regards to the unresolved “missing” carbon sinks due to incomplete knowledge about the role the ocean and forest ecosystems play in global carbon cycle.
2. Global forests with their large quantity of non-photosynthetic woody mass represent a significant carbon pool relative to the size of the atmospheric pool, with coarse woody debris in forests being a potentially large, long-term carbon storage. The importance of this pool in controlling the missing C sink cannot be evaluated until the size and dynamics of this pool are better understood.
3. CWD stores vary significantly in space and time and are controlled by processes of input driven by type, frequency, and severity of disturbance as well as by decomposition driven by climatic and microclimatic variations and substrate quality.
4. CWD decomposition was studied in the Russian boreal forests of the southern taiga zone at four sites located near St.-Petersburg in Northwestern Russia, Krasnoyarsk in Eastern Siberia, Irkutsk in the Baikal region, and Khabarovsk in the Russian Far East. This study was a part of a broader research project assessing processes associated with carbon accumulation, storage, and release by woody detritus in the forests of Russia.

5. CWD decay-class specific characteristics differ among species with large differences observed between conifers and birch. Decay-class specific density differences are associated mostly with decay classes and species and much less determined by regions or position of the CWD. Density declines with decay class. The density differences among the species diminish in advanced decay classes. The density differences related to position are likely to occur in conifers for decay classes two and three.
6. Although decomposition rate-constants show regional differences within each species, they have a similar rank distribution among the species. The order of increasing woody debris decomposition rate-constants (k) among the studied species was birch > spruce > Scotch pine > larch > white pine. The fast decomposition of birch was associated with the lack of decay-resistant heartwood and the presence of bark over the entire decomposition history of this species. The slow decomposition of white pine was associated with the presence of decay-suppressing substances in its heartwood, and the large size, which is closely related to the low surface area to volume ratio and to a low sapwood-to-heartwood ratio.
7. No effect of temperature or precipitation was found on log decomposition rate among the Russian study regions. However, at the global level an effect of temperature on decomposition rates of decay-susceptible species was observed suggesting that these two variables are positively correlated, when substrate quality (due to heartwood resistance) is not limiting.
8. The carbon sequestration potential of Russian forests may be increased through CWD management. The magnitude of this increase associated with changes in species composition is substantial when compared to the

potential increases in carbon sequestration associated with other management steps such as establishing plantations on forest and agricultural lands, reducing stand replacement fires, reducing harvest rates and increasing rotation age, increasing stand productivity via silvicultural treatments, and establishing plantations on sands, drained peat bogs, and mine tailings.

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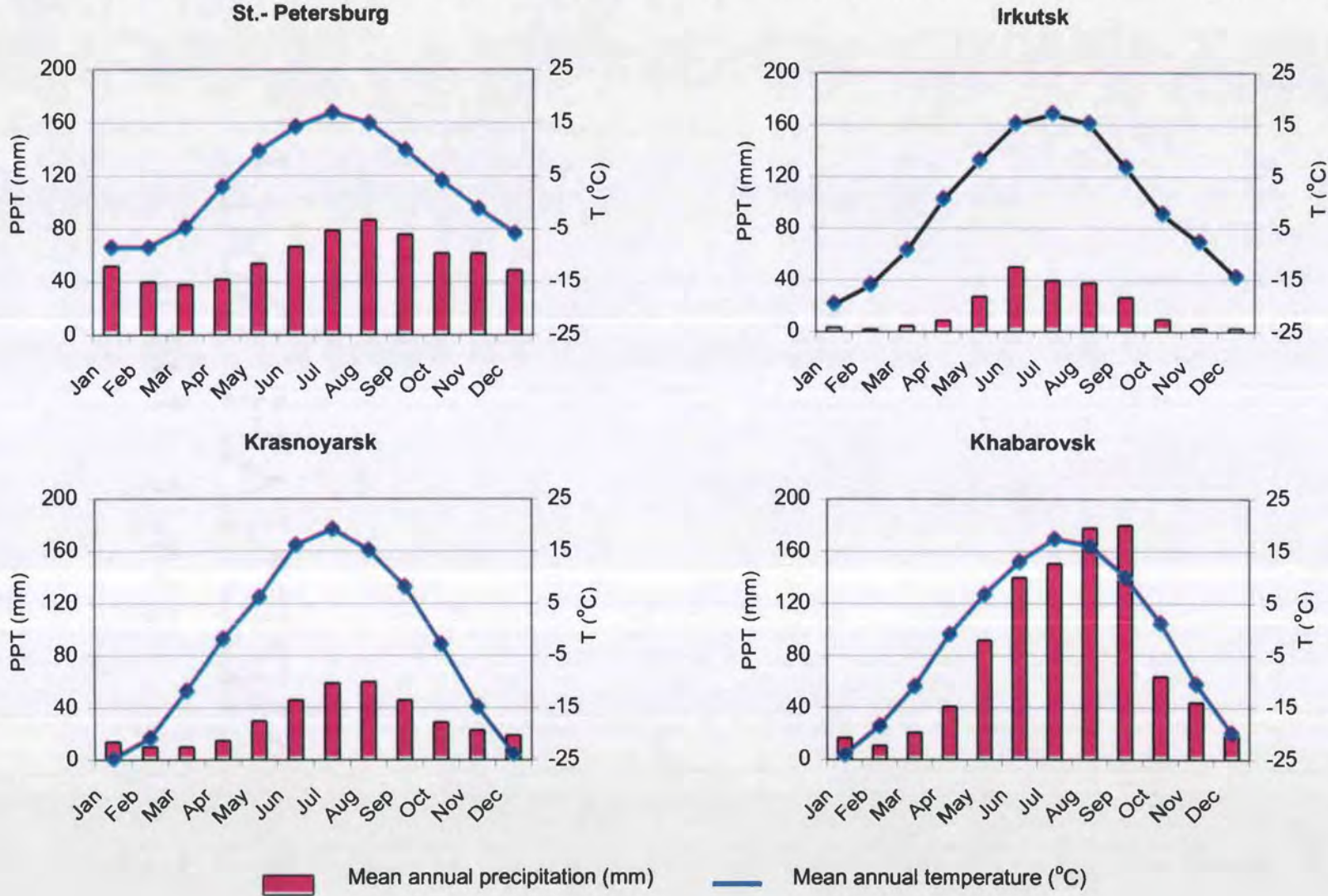
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APPENDICES

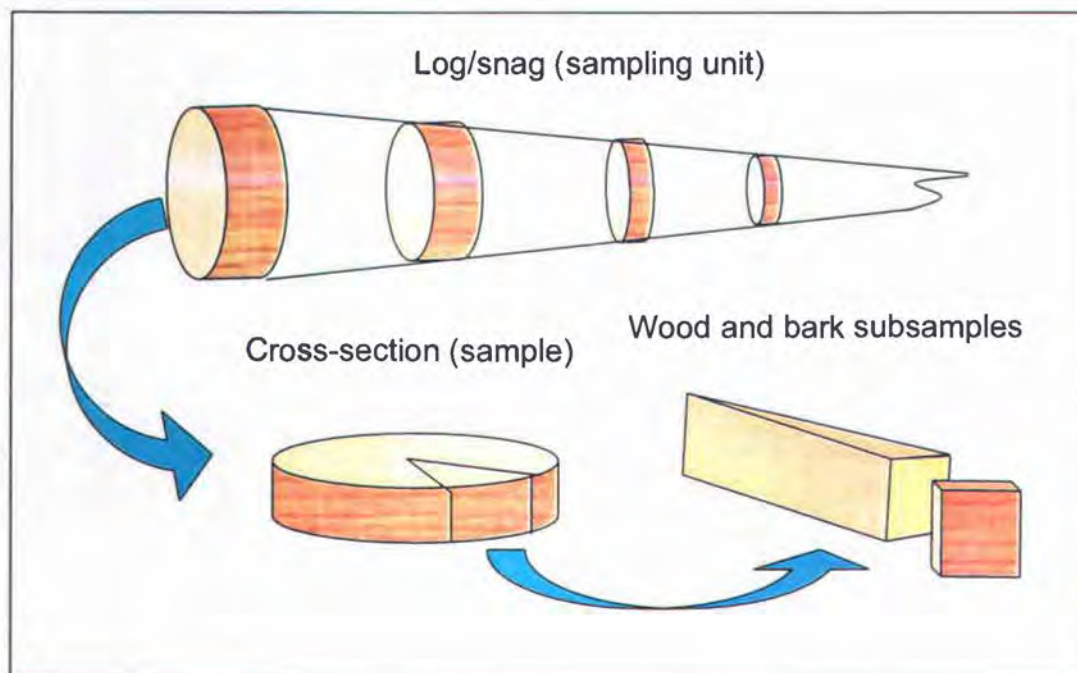
APPENDIX 1: Climate data for the regions of study

Figure 1-1. Comparison of trends in mean monthly temperatures and precipitation patterns among four regions of Russia



APPENDIX 2: Sampling procedure sequence and data sheet formats

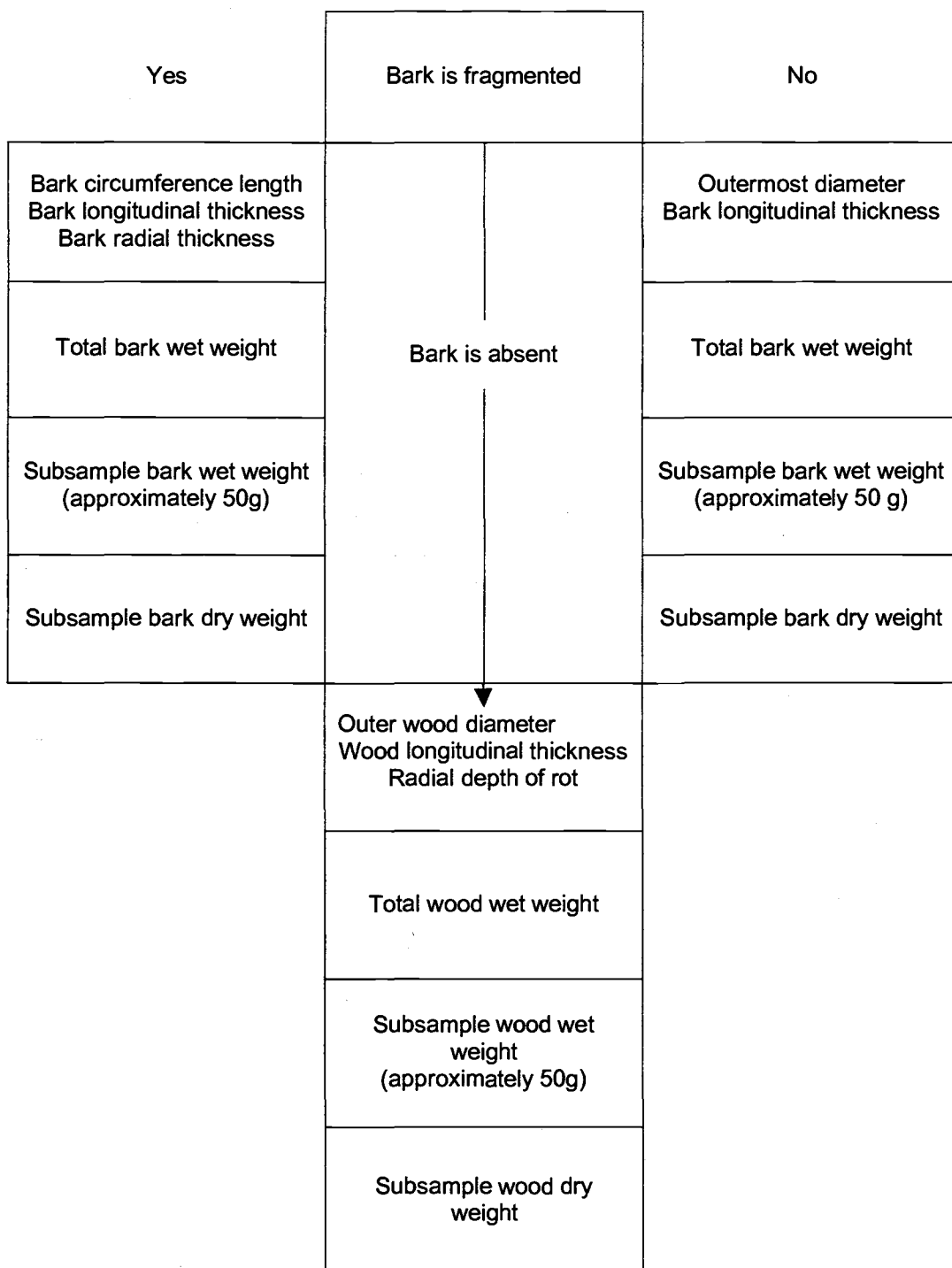
Figure 2-1. CWD sampling procedure and sequence



Sampling procedure sequence:

1. Four cross-sections were cut with a chainsaw equidistant along the CWD pieces.
2. Each cross-section was processed by taking measurements of outermost diameter, bark and wood longitudinal thickness, bark radial thickness, depth of rot penetration into the wood tissues, and by determining weight of bark and wood tissues.
3. Subsamples of bark (representative section) and wood (a wedge) approximately 50 g each were taken (Figure above), and the weight of each was determined.

Figure 2-2. Diagram and a sequence of cross section processing procedure



The above diagram outlines the cross section processing procedure:

1. The bark condition of the cross section was determined.
2. If the bark was intact (the "NO" branch), the outmost diameter of cross-section, average bark longitudinal thickness, and average inner bark radial thickness (if possible) were recorded.
3. If the bark was fragmented (the "YES" branch), average bark circumferential length, longitudinal thickness, total bark radial thickness, and inner bark radial thickness (if possible) were recorded.
4. If there was no bark on bole (the "BARK IS ABSENT" branch), all steps related to bark were skipped until step No. 8 of this outline.
5. Bark was separated from the wood and total bark wet weight was recorded.
6. If total bark wet weight exceeded 70g, a representative bark sub-sample (around 50g) was selected and weighed. The weight was recorded as bark wet sub-sample weight.
7. If the total bark weight fluctuated between 50g and 70g, the bark total weight was recorded as bark wet sub-sample weight with 0.1g precision.
8. Outer wood diameter, average wood longitudinal thickness, radial depth of rot, and average hollow diameter were recorded. For the extremely decayed cross-sections, the external dimensions prior to removal of the section from the log were recorded.
9. Total wood wet weight was determined.
10. If total wood wet weight exceeded 70g, a representative (around 50g) wood sub-sample was selected and weighed. The weight was recorded as wood wet sub-sample weight.
11. If total wood weight fluctuated between 50g and 70g (150g for mushy sections), the wood total weight was recorded as wood wet sub-sample weight.

12. Sub-samples of both bark and wood were placed in the separate cloth bags. Each cloth bag was marked indicating the location, the sampled log's number (1, 2, ..., n), the sampled cross section's number (A, B, C, or D), and type of collected tissue (bark or wood).
13. The cloth bags with collected sub-samples were air-dried in a dry, warm place (attic) until the end of the field season. For the transportation, all the sub-samples were placed into large plastic bags to prevent accidental wetting, and into heavy-duty bags to prevent transportation damage and loss. At the end of the field season, all the sub-samples were transported to the regional Forest Inventory Enterprise (FIE) headquarters. Then, they undergone a heat treatment for three hours at 70°C at one of the facilities equipped for this purpose at Forestry Institute, Academy, or Pest Management Station. The heat treatment of the woody material was required by USDA-APHIS to prevent the disease and pest introduction to the U.S. snag.
14. The final stage of the sub-sample processing took place at Oregon State University's forest ecology lab. They were placed in drying ovens and dried at 55°C until their weights were stabilized (the daily weight loss did not exceed 0.1g).
15. Each sample was then removed from the cloth bag and dry sample weight was recorded. The cloth bags did not have a uniform weight, therefore extraction of samples from the bags eliminated the error of bag weight difference. The time spent between the sample bag left the oven and sample weight was determined, did not exceed 1.5 minutes to avoid the weight gain by the sample due to process of moisture absorption.
16. The sub-samples were saved for carbon and nutrient analysis.

Figure 2-3. Format one data sheet

Wood Decomposition Project (Ver 1.5 , file TD22_WFW.DOC)
Log/Snag Description

Studyid TD22 Format 1 Names _____

Date _____ Site _____ Plot _____ Log Number _____

Forest Type _____ ReSample: Y/N Current Vol.=Initial Vol.: Y/N

Species _____ Position Log/Snag Decay class _____

Age _____ years Method _____ Cause of Death _____

Whole Tree / Partial Tree Standing Snag Height _____ m

DBH _____ cm Diameter at Base (max) _____ cm (min) _____ cm
 AAAAAAAAAA
 AAAAAAAAAA Diameter at Top (max) _____ cm (min) _____ cm

If DBH unknown
 enter 'E'
 and see back

Total Length _____ m Bark Cover _____ %

Volume Missing From Rot _____ cubic meters

Diam.1st Sample (max) _____ cm	(min) _____ cm	Height _____ m	Whole Tree heights from base
Diam.2nd Sample (max) _____ cm	(min) _____ cm	Height _____ m	
Diam.3rd Sample (max) _____ cm	(min) _____ cm	Height _____ m	Partial Tree heights from large end
Diam.4th Sample (max) _____ cm	(min) _____ cm	Height _____ m	
Diam.5th Sample (max) _____ cm	(min) _____ cm	Height _____ m	

FRAGMENTATION INDICATORS

leaves present	Y/N	color _____
twigs present	Y/N	
branches present	Y/N	can not support own weight log x-section elliptical
bark on branches	Y/N	
bark on bole	Y/N	
sapwood sloughing	Y/N	
log collapsing	Y/N	
log scattered	Y/N	

BIOTIC INDICATORS

conks present	Y/N	percent cover _____ %
moss covering log	Y/N	
lichens covering	Y/N	percent cover _____ %
carpenter ants	Y/N	where? _____
termites	Y/N	
bark beetle Gal.	Y/N	
bear damage	Y/N	
brown rot	Y/N	

Continued:

white rot Y/N
 sapwood friable Y/N
 heartwood friable Y/N
 casehardening Y/N
 branch stubs move Y/N
 wood borers Y/N

where? _____

can crush with hand

can crush with hand

Notes:

Format one data sheet (backside):

Initial Volume Calculation without DBH

choose only one of the following options:

- Basal Diameter from stump with bark (max) _____ cm (min) _____ cm
- Basal Diameter from stump w/o bark (max) _____ cm (min) _____ cm
- DBH w/o bark (max) _____ cm (min) _____ cm
 Radial Bark thickness _____ mm
- DBH w/o bark and with wood fragmentation loss
 (max) _____ cm (min) _____ cm
 Missing Radial Wood Thickness _____ cm Radial Bark thickness _____ mm
- Good outside Bark Diameter (max) _____ cm (min) _____ cm
 at height of _____ m from tree base
- Unable to determine DBH by any method, check here _____

Notes:

APPENDIIX 3: CWD age and diameter range distributions

Table 3-1. Age range of CWD sampled for each decay class and species

Decay classes	Species					
	<i>Betula costata</i>	<i>Betula pendula</i>	<i>Larix</i> spp.	<i>Pinus sylvestris</i>	<i>P. siberica/ koraiensis</i>	<i>Picea</i> spp.
1	1 - 8	0 - 7	0 - 11	0 - 9	0 - 8	0 - 8
2	11 - 12	2 - 15	4 - 25	1 - 19	7 - 65	2 - 15
3	13 - 22	5 - 33	13 - 104	8 - 40	21 - 77	5 - 71
4	22 - 77	11 - 33	30 - 104	17 - 70	39 - 160	16 - 77
5	77	24 - 73	90 - 110	40 - 70	65 - 135	30 - 77

Table 3-2. Base diameter distribution among the regions and species

Species	Regions	Snags			Logs		
		Mean (SE)	Min	Max	Mean (SE)	Min	Max
<i>Betula pendula</i>	St.-Petersburg	---	---	---	25 (0)*	25	25
	Krasnoyarsk	32 (3)	16	57	26 (2)	14	57
	Irkutsk	30 (2)	21	57	31 (1)	12	52
<i>Betula costata</i>	Khabarovsk	21(2)	16	31	21 (1)	12	32
	Khabarovsk	30 (3)	24	44	36 (3)	12	70
<i>Picea abies</i>	St.-Petersburg	---	---	---	14 (2)	11	20
<i>P. obovata</i>	Krasnoyarsk	34 (2)	26	41	34 (1)	17	51
<i>P. ajanensis</i>	Khabarovsk	27 (2)	17	47	34 (2)	15	63
<i>Pinus sylvestris</i>	St.-Petersburg	25 (3)*	22	27	18 (2)	11	46
	Krasnoyarsk	41 (2)	29	48	30 (2)	13	64
	Irkutsk	35 (2)	23	48	33 (2)	19	66
<i>Larix siberica</i>	Krasnoyarsk	56 (2)	46	65	40 (3)	11	70
	Irkutsk	38 (2)	25	63	40 (3)	18	120
<i>Log. dahurica</i>	Khabarovsk	25 (2)	16	35	30 (2)	17	53
<i>Pinus siberica</i>	Irkutsk	40 (2)	26	57	32 (1)	17	52
<i>P. koraiensis</i>	Khabarovsk	41 (6)	17	74	55 (4)	23	120

APPENDIX 4: CWD decomposition rate constants

Table 4-1. Coefficients of regressions used to estimate decomposition rate constants for studied species in four regions of Russia using percent mass remaining and an intercept of 100 percent.

Species	Regions	Regression coefficients ^a							
		Snags				Logs			
		Y ₀ (%)	k (year ⁻¹)	N	Adj. r ²	Y ₀ (%)	k (year ⁻¹)	N	Adj. r ²
<i>Betula pendula</i>	St.-Petersburg	100	-0.037 (0.007)	7	0.81	100	-0.054 (0.013)	11	0.62
	Krasnoyarsk	100	-0.051 (0.005)	13	0.89	100	-0.058 (0.003)	28	0.93
	Irkutsk	100	-0.039 (0.006)	17	0.72	100	-0.047 (0.002)	41	0.91
<i>Betula costata</i>	Khabarovsk	100	-0.052 (0.011)	7	0.76	100	-0.069 (0.005)	20	0.92
	Khabarovsk	100	-0.063 (0.004)	7	0.97	100	-0.036 (0.003)	23	0.89
<i>Picea abies</i>	St.-Petersburg	100	-0.014 (0.009)*	6	0.19	100	-0.032 (0.003)	20	0.86
<i>P. obovata</i>	Krasnoyarsk	100	-0.0006 (0.002)*	8	-0.13	100	-0.045 (0.003)	31	0.87
<i>P. ajanensis</i>	Khabarovsk	100	-0.031 (0.003)	14	0.89	100	-0.029 (0.001)	39	0.92
<i>Pinus sylvestris</i>	St.-Petersburg	100	-0.032 (0.005)	14	0.72	100	-0.033 (0.003)	42	0.74
	Krasnoyarsk	100	+0.009 (0.010)*	8	-0.03	100	-0.038 (0.002)	31	0.93
	Irkutsk	100	-0.001 (0.002)*	19	-0.03	100	-0.032 (0.002)	35	0.90
<i>Larix siberica</i>	Krasnoyarsk	100	-0.003 (0.003)*	8	0.002	100	-0.025 (0.001)	30	0.93
	Irkutsk	100	-0.010 (0.001)	28	0.80	100	-0.031 (0.002)	42	0.90
<i>Larix dahurica</i>	Khabarovsk	100	-0.013 (0.003)	10	0.67	100	-0.019 (0.002)	26	0.76
<i>Pinus siberica</i>	Irkutsk	100	-0.006 (0.001)	17	0.72	100	-0.021 (0.002)	33	0.86
<i>P. koraiensis</i>	Khabarovsk	100	-0.009 (0.002)	12	0.58	100	-0.017 (0.001)	35	0.92

^a The regression was of the form $Y_t = Y_0 e^{-kt}$ where Y_t is the percentage of the density remaining at time t (years), Y_0 is the initial mass in percent dry weight, and k is the decomposition rate constant

* The coefficient is not significantly different from zero at alpha 0.05 level

Table 4-2. Coefficients of regressions used to estimate decomposition rate constants for logs and snags combined for studied species in four regions of Russia using percent mass remaining and an intercept of 100 percent

Species	Regions	Regression coefficients ^a							
		Regular intercept				Intercept forced through 100			
		Y ₀ (%)	k (year ⁻¹)	N	Adj. r ²	Y ₀ (%)	k (year ⁻¹)	N	Adj. r ²
<i>Betula pendula</i>	St.-Petersburg	70.99	-0.035 (0.013)	18	0.26	100	-0.053 (0.009)	18	0.63
	Krasnoyarsk	108.37	-0.061 (0.004)	41	0.84	100	-0.057 (0.002)	41	0.93
	Irkutsk	95.59	-0.045 (0.003)	58	0.81	100	-0.047 (0.002)	58	0.91
	Khabarovsk	124.08	-0.079 (0.007)	27	0.82	100	-0.067 (0.004)	27	0.90
<i>Betula costata</i>	Khabarovsk	83.69	-0.032 (0.003)	30	0.82	100	-0.036 (0.002)	30	0.89
<i>Picea abies</i>	St.-Petersburg	89.98	-0.028 (0.003)	26	0.75	100	-0.032 (0.003)	26	0.85
<i>P. obovata</i>	Krasnoyarsk	119.09	-0.050 (0.006)	39	0.68	100	-0.043 (0.003)	39	0.82
<i>P. ajanensis</i>	Khabarovsk	105.83	-0.030 (0.002)	53	0.86	100	-0.029 (0.001)	53	0.91
<i>Pinus sylvestris</i>	St.-Petersburg	88.98	-0.029 (0.004)	56	0.54	100	-0.033 (0.003)	56	0.74
	Krasnoyarsk	111.88	-0.042 (0.003)	39	0.88	100	-0.038 (0.002)	39	0.93
	Irkutsk	116.69	-0.035 (0.002)	54	0.80	100	-0.029 (0.002)	54	0.82
<i>Larix siberica</i>	Krasnoyarsk	98.29	-0.024 (0.002)	38	0.87	100	-0.024 (0.001)	38	0.92
	Irkutsk	108.34	-0.026 (0.002)	70	0.64	100	-0.024 (0.002)	70	0.77
<i>Larix dahurica</i>	Khabarovsk	86.46	-0.015 (0.002)	36	0.61	100	-0.018 (0.002)	36	0.75
<i>Pinus siberica</i>	Irkutsk	92.60	-0.016 (0.002)	50	0.51	100	-0.018 (0.001)	50	0.75
<i>P. koraiensis</i>	Khabarovsk	91.40	-0.015 (0.001)	47	0.85	100	-0.017 (0.001)	47	0.90

^a The regression was of the form $Y_t = Y_0 e^{-kt}$ where Y_t is the percentage of the density remaining at time t (years), Y_0 is the initial mass in percent dry weight, and k is the decomposition rate constant

Table 4-3. Decomposition rate comparisons (SE's in parenthesis) based on species group comparisons within each region

Regions	Species	Snags	Grouping*		Logs	Grouping*	
			0.05	0.01		0.05	0.01
St.-Petersburg	<i>Betula pendula</i>	-0.027 (0.011)	A	A	-0.054 (0.013)	A	A
	<i>Picea abies</i>	-0.044 (0.022)	A	A	-0.026 (0.007)	B	AB
	<i>Pinus sylvestris</i>	-0.037 (0.008)	A	A	-0.027 (0.004)	B	B
Krasnoyarsk	<i>Betula pendula</i>	-0.056 (0.006)	A	A	-0.061 (0.006)	A	A
	<i>Larix siberica</i>	-0.004 (0.006)	B	B	-0.023 (0.002)	B	B
	<i>Picea obovata</i>	+0.0006 (0.0076)	B	B	-0.049 (0.006)	AC	A
	<i>Pinus sylvestris</i>	+0.020 (0.037)	AB	AB	-0.044 (0.004)	C	A
Irkutsk	<i>Betula pendula</i>	-0.052 (0.010)	A	A	-0.042 (0.004)	A	A
	<i>Larix siberica</i>	-0.010 (0.001)	B	B	-0.031 (0.002)	B	A
	<i>Pinus siberica</i>	-0.003 (0.001)	C	C	-0.019 (0.002)	C	B
	<i>Pinus sylvestris</i>	-0.004 (0.004)	BC	BC	-0.036 (0.004)	AB	A
Khabarovsk	<i>Betula costata</i>	-0.071 (0.013)	A	A	-0.030 (0.003)	A	A
	<i>Betula pendula</i>	-0.077 (0.015)	A	AD	-0.078 (0.008)	B	B
	<i>Larix dahurica</i>	-0.009 (0.015)	BC	BC	-0.015 (0.002)	C	C
	<i>Picea ajanensis</i>	-0.035 (0.002)	B	BD	-0.028 (0.002)	A	A
	<i>Pinus koraiensis</i>	-0.003 (0.004)	C	C	-0.015 (0.001)	C	C

* Same letter within a region indicates a lack of significant differences among the species decomposition rates at supplied alpha levels

**APPENDIX 5: Decay class specific densities by region and species and
their comparisons**

Table 5-1. Mean densities (g/cm³), SE's (in parenthesis), and number of observations (N) of *Abies siberica* CWD by decay class, position, and region

Decay Class	Position	Region			
		Novosibirsk		Krasnoyarsk	
		Mean (SE), (g/cm ³)	N	Mean (SE), (g/cm ³)	N
1	Log	0.262	1	0.234	1
	Snag	0.327 (0.024)	3	0.272 (0.020)	4
2	Log	0.322 (0.016)	3	0.298 (0.039)	2
	Snag	0.306 (0.025)	2	0.355 (0.025)	2
3	Log	0.318 (0.007)	3	0.195 (0.013)	4
	Snag	0.322	1	—	—
4	Log	0.255 (0.025)	5	0.154 (0.010)	5
	Snag	—	—	—	—
5	Log	0.231 (0.078)	2	0.150 (0.015)	5
	Snag	—	—	—	—

Table 5-2. Mean densities (g/cm³), SE's (in parenthesis), and number of observations (N) of *Betula costata* CWD by decay class, position, and region

Decay Class	Position	Region	
		Khabarovsk	
		Mean (SE), (g/cm ³)	N
1	Log	0.501 (0.006)	8
	Snag	0.540 (0.007)	5
2	Log	0.333 (0.037)	3
	Snag	—	—
3	Log	0.184 (0.012)	8
	Snag	0.235 (0.003)	2
4	Log	0.120 (0.005)	2
	Snag	—	—
5	Log	0.084 (0.003)	2
	Snag	—	—

Table 5-3. Mean densities (g/cm³), SE's (in parenthesis), and number of observations (N) of *Betula pendula* CWD by decay class, position, and region

Decay Class	Position	Regions											
		St.-Petersburg		Nizhnii Novgorod		Novosibirsk		Krasnoyarsk		Irkutsk		Khabarovsk	
		Mean (SE)	N	Mean (SE)	N	Mean (SE)	N	Mean (SE)	N	Mean (SE)	N	Mean (SE)	N
1	Log	0.502	1	0.451	3	0.442	5	0.509	4	0.463	8	0.478	4
	Snag	---	---	(0.024)	---	---	---	(0.006)	---	(0.008)	---	(0.016)	---
	Log	0.475	4	---	---	(0.026)	1	0.494	5	0.472	9	0.508	2
	Snag	(0.010)	---	---	---	0.468	---	(0.016)	---	(0.005)	---	(0.028)	---
2	Log	0.426	1	0.390	4	0.410	5	0.398	4	0.307	8	0.358	6
	Snag	---	---	(0.016)	---	(0.036)	---	(0.005)	---	(0.013)	---	(0.017)	---
	Log	0.445	4	---	---	0.359	2	0.378	3	0.361	8	0.344	3
	Snag	(0.021)	---	---	---	(0.056)	---	(0.018)	---	(0.017)	---	(0.080)	---
3	Log	0.235	5	0.210	4	0.221	4	0.288	5	0.231	6	0.213	3
	Snag	(0.040)	---	(0.034)	---	(0.056)	---	(0.034)	---	(0.031)	---	(0.019)	---
	Log	0.236	2	---	---	---	---	0.217	3	---	---	0.278	2
	Snag	(0.153)	---	---	---	---	---	(0.014)	---	---	---	(0.058)	---
4	Log	0.137	9	0.099	4	0.252	6	0.159	6	0.115	11	0.117	5
	Snag	(0.022)	---	(0.018)	---	(0.061)	---	(0.022)	---	(0.005)	---	(0.016)	---
	Log	---	---	---	---	---	---	0.204	2	---	---	---	---
	Snag	---	---	---	---	---	---	(0.026)	---	---	---	---	---
5	Log	0.094	2	---	---	0.157	7	0.093	9	0.095	8	0.086	3
	Snag	(0.003)	---	---	---	(0.034)	---	(0.006)	---	(0.010)	---	(0.016)	---
	Log	---	---	---	---	---	---	---	---	---	---	---	---
	Snag	---	---	---	---	---	---	---	---	---	---	---	---

Table 5-4. Mean densities (g/cm³), SE's (in parenthesis), and number of observations (N) of *Larix* spp. CWD by decay class, position, and region

Decay Class	Position	Region					
		Krasnoyarsk		Irkutsk		Khabarovsk	
		Mean (SE), (g/cm ³)	N	Mean (SE), (g/cm ³)	N	Mean (SE), (g/cm ³)	N
1	Log	0.475 (0.005)	4	0.456 (0.017)	12	0.455 (0.012)	13
	Snag	0.452 (0.011)	4	0.447 (0.016)	8	0.443 (0.006)	2
2	Log	0.416 (0.014)	5	0.390 (0.008)	8	0.389 (0.015)	13
	Snag	0.448 (0.023)	4	0.475 (0.022)	7	0.465 (0.027)	8
3	Log	0.305 (0.030)	7	0.366 (0.016)	9	0.318 (0.018)	13
	Snag	---	---	0.461 (0.010)	12	---	---
4	Log	0.146 (0.012)	8	0.151 (0.010)	8	0.185 (0.013)	9
	Snag	---	---	---	---	---	---
5	Log	0.087 (0.006)	8	0.130 (0.011)	8	0.110 (0.024)	4
	Snag	---	---	---	---	---	---

Table 5-5. Mean densities (g/cm³), SE's (in parenthesis), and number of observations (N) of *Picea* spp. CWD by decay class, position, and region

Decay Class	Position	Regions							
		St.-Petersburg		Krasnoyarsk		Irkutsk		Khabarovsk	
		Mean (SE), (g/cm ³)	N	Mean (SE), (g/cm ³)	N	Mean (SE), (g/cm ³)	N	Mean (SE), (g/cm ³)	N
1	Log	0.327 (0.013)	5	0.361 (0.009)	4	0.374 (0.017)	6	0.341 (0.011)	11
	Snag	0.373 (0.032)	4	0.364 (0.015)	4	---	---	0.377 (0.006)	8
2	Log	0.270 (0.012)	6	0.337 (0.012)	4	0.322 (0.034)	6	0.324 (0.018)	11
	Snag	0.374 (0.015)	5	0.387 (0.010)	4	---	---	0.392 (0.009)	3
3	Log	0.210 (0.019)	7	0.270 (0.014)	8	0.215 (0.010)	6	0.238 (0.020)	15
	Snag	---	---	---	---	---	---	0.234 (0.067)	3
4	Log	0.134 (0.045)	3	0.145 (0.011)	9	0.100 (0.015)	4	0.150 (0.018)	10
	Snag	---	---	---	---	---	---	---	---
5	Log	---	---	0.099 (0.008)	8	---	---	0.119 (0.007)	6
	Snag	---	---	---	---	---	---	---	---

Table 5-6. Mean densities (g/cm³), SE's (in parenthesis), and number of observations (N) of *Pinus siberica/koraiensis* CWD by decay class, position, and region

Decay Class	Position	Regions			
		Irkutsk		Khabarovsk	
		Mean (SE), (g/cm ³)	N	Mean (SE), (g/cm ³)	N
1	Log	0.332 (0.009)	8	0.349 (0.008)	8
	Snag	0.332 (0.006)	8	0.327 (0.031)	5
2	Log	0.298 (0.011)	8	0.316 (0.012)	10
	Snag	0.345 (0.004)	7	0.342 (0.018)	5
3	Log	0.227 (0.016)	8	0.241 (0.012)	12
	Snag	0.304 (0.005)	2	0.333 (0.021)	3
4	Log	0.140 (0.011)	8	0.158 (0.011)	4
	Snag	---	---	---	---
5	Log	0.104 (0.006)	8	0.131 (0.027)	2
	Snag	---	---	---	---

Table 5-7. Mean densities (g/cm³), SE's (in parenthesis), and number of observations (N) of *Pinus sylvestris* CWD by decay class, position, and region

Decay Class	Position	Regions							
		St.-Petersburg		Novosibirsk		Krasnoyarsk		Irkutsk	
		Mean (SE), (g/cm ³)	N	Mean (SE), (g/cm ³)	N	Mean (SE), (g/cm ³)	N	Mean (SE), (g/cm ³)	N
1	Log	0.411 (0.009)	2	0.353 (0.020)	2	0.351 (0.013)	8	0.350 (0.008)	8
	Snag	0.384 (0.008)	6	0.342 (0.045)	2	0.355 (0.006)	5	0.367 (0.011)	10
2	Log	0.332 (0.016)	12	0.322 (0.012)	4	0.340 (0.011)	3	0.307 (0.013)	12
	Snag	0.367 (0.020)	4	---	---	0.362 (0.013)	5	0.365 (0.009)	10
3	Log	0.240 (0.012)	21	0.299 (0.037)	3	0.312 (0.018)	10	0.262 (0.016)	13
	Snag	0.270 (0.043)	2	0.375	1	---	---	0.321	1
4	Log	0.121 (0.016)	5	0.289 (0.039)	4	0.179 (0.014)	12	0.143 (0.013)	10
	Snag	---	---	---	---	---	---	---	---
5	Log	0.108 (0.004)	3	0.163 (0.018)	4	0.114 (0.012)	11	0.119 (0.007)	11
	Snag	---	---	---	---	---	---	---	---

Table 5-8. Mean densities (g/cm³), SE's (in parenthesis), and number of observations (N) of *Populus tremula* CWD by decay class, position, and region

Decay Class	Position	Regions					
		St.-Petersburg		Moskow		Khabarovsk	
		Mean (SE), (g/cm ³)	N	Mean (SE), (g/cm ³)	N	Mean (SE), (g/cm ³)	N
1	Log	0.294 (0.043)	3	0.365 (0.010)	4	0.354 (0.012)	2
	Snag	—	—	—	—	—	—
2	Log	0.278 (0.052)	3	0.306 (0.022)	7	0.256 (0.074)	2
	Snag	—	—	—	—	—	—
3	Log	0.172 (0.015)	4	0.291 (0.026)	7	—	—
	Snag	0.236	1	—	—	0.246	1
4	Log	0.113	1	0.151	1	0.141	1
	Snag	—	—	—	—	—	—
5	Log	—	—	—	—	—	—
	Snag	—	—	—	—	—	—

Table 5-9. The comparison of *Abies siberica* log and snag estimates of mean density within decay class and region

Decay Class	Position	Region			
		Novosibirsk		Krasnoyarsk	
		Mean, (g/cm ³)	Parewise comparison	Mean, (g/cm ³)	Parewise comparison
1	Log	0.262	A	0.234	A
	Snag	0.327	A	0.272	A
2	Log	0.322	A	0.298	A
	Snag	0.306	A	0.355	A
3	Log	0.318	A	0.195	N/A
	Snag	0.322	A	—	N/A

Table 5-10. The comparison of *Betula costata* log and snag estimates of mean density within decay class and region

Decay Class	Position	Region	
		Khabarovsk	
		Mean, (g/cm ³)	Parewise comparison
1	Log	0.501	A
	Snag	0.540	B
2	Log	0.333	N/A
	Snag	—	N/A
3	Log	0.184	A
	Snag	0.235	A

Table 5-11. The comparison of *Betula pendula* log and snag estimates of mean density within decay class and region

Decay Class	Position	Regions											
		St.-Petersburg		Nizhnii Novgorod		Novosibirsk		Krasnoyarsk		Irkutsk		Khabarovsk	
		Mean, (g/cm ³)	Parewise Compa-rison	Mean, (g/cm ³)	Parewise Compa-rison	Mean, (g/cm ³)	Parewise Compa-rison	Mean, (g/cm ³)	Parewise Compa-rison	Mean, (g/cm ³)	Parewise Compa-rison	Mean, (g/cm ³)	Parewise Compa-rison
1	Log	0.502	A	0.451	N/A	0.442	A	0.509	A	0.463	A	0.478	A
	Snag	0.475	A	---	N/A	0.468	A	0.494	A	0.472	A	0.508	A
2	Log	0.426	A	0.390	N/A	0.410	A	0.398	A	0.307	A	0.358	A
	Snag	0.445	A	---	N/A	0.359	A	0.378	A	0.361	B	0.344	A
3	Log	0.235	A	0.210	N/A	0.221	N/A	0.288	A	0.231	N/A	0.213	A
	Snag	0.236	A	---	N/A	---	N/A	0.217	A	---	N/A	0.278	A

Table 5-12. The comparison of *Larix* spp. log and snag estimates of mean density within decay class and region

Decay Class	Position	Region					
		Krasnoyarsk		Irkutsk		Khabarovsk	
		Mean, (g/cm ³)	Parewise comparison	Mean, (g/cm ³)	Parewise comparison	Mean, (g/cm ³)	Parewise comparison
1	Log	0.475	A	0.456	A	0.455	A
	Snag	0.452	A	0.447	A	0.443	A
2	Log	0.416	A	0.390	A	0.389	A
	Snag	0.448	A	0.475	B	0.465	B
3	Log	0.305	N/A	0.366	A	0.318	N/A
	Snag	---	N/A	0.461	B	---	N/A

Table 5-13. The comparison of *Picea* spp. log and snag estimates of mean density within decay class and region

Decay Class	Position	Region							
		St.-Petersburg		Krasnoyarsk		Irkutsk		Khabarovsk	
		Mean, (g/cm ³)	Parewise comparison	Mean, (g/cm ³)	Parewise comparison	Mean, (g/cm ³)	Parewise comparison	Mean, (g/cm ³)	Parewise comparison
1	Log	0.327	A	0.361	A	0.374	N/A	0.341	A
	Snag	0.373	A	0.364	A	---	N/A	0.377	B
2	Log	0.270	A	0.337	A	0.322	N/A	0.324	A
	Snag	0.374	B	0.387	B	---	N/A	0.392	A
3	Log	0.210	N/A	0.270	N/A	0.215	N/A	0.238	A
	Snag	---	N/A	---	N/A	---	N/A	0.234	A

Table 5-14. The comparison of *Pinus siberica/koraiensis* log and snag estimates of mean density within decay class and region

Decay Class	Position	Regions			
		Irkutsk		Khabarovsk	
		Mean, (g/cm ³)	Parewise comparison	Mean, (g/cm ³)	Parewise comparison
1	Log	0.332	A	0.349	A
	Snag	0.332	A	0.327	A
2	Log	0.298	A	0.316	A
	Snag	0.345	B	0.342	A
3	Log	0.227	A	0.241	A
	Snag	0.304	A	0.333	B

Table 5-15. The comparison of *Pinus sylvestris* log and snag estimates of mean density within decay class and region

Decay Class	Position	Regions							
		St.-Petersburg		Novosibirsk		Krasnoyarsk		Irkutsk	
		Mean, (g/cm ³)	Parewise comparison	Mean, (g/cm ³)	Parewise comparison	Mean, (g/cm ³)	Parewise comparison	Mean, (g/cm ³)	Parewise comparison
1	Log	0.411	A	0.353	A	0.351	A	0.350	A
	Snag	0.384	A	0.342	A	0.355	A	0.367	A
2	Log	0.332	A	0.322	N/A	0.340	A	0.307	A
	Snag	0.367	A	---	N/A	0.362	A	0.365	B
3	Log	0.240	A	0.299	A	0.312	N/A	0.262	N/A
	Snag	0.270	A	0.375	A	---	N/A	0.321	N/A

Table 5-16. The comparison of *Populus tremula* log and snag estimates of mean density within decay class and region

Decay Class	Position	Regions					
		St.-Petersburg		Moscow		Khabarovsk	
		Mean, (g/cm ³)	Parewise comparison	Mean, (g/cm ³)	Parewise comparison	Mean, (g/cm ³)	Parewise comparison
1	Log	0.294	N/A	0.365	N/A	0.354	N/A
	Snag	---	N/A	---	N/A	---	N/A
2	Log	0.278	N/A	0.306	N/A	0.256	A
	Snag	---	N/A	---	N/A	0.246	A
3	Log	0.172	A	0.291	N/A	---	N/A
	Snag	0.236	A	---	N/A	---	N/A

Table 5-17. Comparison of the *Abies siberica* estimates of mean density among regions for decay class and position

Decay Class		Position	Region	
			Novosibirsk	Krasnoyarsk
1	Log	Mean, (g/cm ³)	0.262	0.234
		Tukey grouping	N/A	N/A
	Snag	Mean, (g/cm ³)	0.327	0.272
		Tukey grouping	A	A
2	Log	Mean, (g/cm ³)	0.322	0.298
		Tukey grouping	A	A
	Snag	Mean, (g/cm ³)	0.306	0.355
		Tukey grouping	A	A
3	Log	Mean, (g/cm ³)	0.318	0.195
		Tukey grouping	A	B
4	Log	Mean, (g/cm ³)	0.255	0.154
		Tukey grouping	A	B
5	Log	Mean, (g/cm ³)	0.231	0.150
		Tukey grouping	A	A

Table 5-18. Comparison of the *Betula pendula* estimates of mean density among regions for decay class and position

Decay Class		Position	Regions					
			St.-Petersburg	N. Novgorod	Novosibirsk	Krasnoyarsk	Irkutsk	Khabarovsk
1	Log	Mean, (g/cm ³) Tukey grouping	0.502 A	0.451 A	0.442 A	0.509 A	0.463 A	0.478 A
	Sna g	Mean, (g/cm ³) Tukey grouping	0.475 A	N/A N/A	0.468 A	0.494 A	0.472 A	0.508 A
2	Log	Mean, (g/cm ³) Tukey grouping	0.426 AB	0.390 AB	0.410 B	0.398 B	0.307 A	0.358 AB
	Sna g	Mean, (g/cm ³) Tukey grouping	0.445 A	N/A N/A	0.359 A	0.378 A	0.361 A	0.344 A
3	Log	Mean, (g/cm ³) Tukey grouping	0.235 A	0.210 A	0.221 A	0.288 A	0.231 A	0.213 A
	Sna g	Mean, (g/cm ³) Tukey grouping	0.236 A	N/A N/A	N/A N/A	0.217 A	N/A N/A	0.278 A
4	Log	Mean, (g/cm ³) Tukey grouping	0.137 A	0.099 A	0.252 B	0.159 AB	0.115 A	0.117 A
5	Log	Mean, (g/cm ³) Tukey grouping	0.094 A	N/A N/A	0.157 A	0.093 A	0.095 A	0.086 A

Table 5-19. Comparison of the *Larix* spp. estimates of mean density among regions for decay class and position

Decay Class		Position	Regions		
			Krasnoyarsk	Irkutsk	Khabarovsk
1	Log	Mean, (g/cm ³)	0.475	0.456	0.455
		Tukey grouping	A	A	A
	Snag	Mean, (g/cm ³)	0.452	0.447	0.443
		Tukey grouping	A	A	A
2	Log	Mean, (g/cm ³)	0.416	0.390	0.389
		Tukey grouping	A	A	A
	Snag	Mean, (g/cm ³)	0.448	0.475	0.465
		Tukey grouping	A	A	A
3	Log	Mean, (g/cm ³)	0.305	0.366	0.318
		Tukey grouping	A	A	A
4	Log	Mean, (g/cm ³)	0.146	0.151	0.185
		Tukey grouping	A	A	A
5	Log	Mean, (g/cm ³)	0.087	0.130	0.110
		Tukey grouping	B	A	AB

Table 5-20. Comparison of the *Picea* spp. estimates of mean density among regions for decay class and position

Decay Class	Position	Region			
		St.-Petersburg	Krasnoyarsk	Irkutsk	Khabarovsk
1	Log	Mean, (g/cm ³)	0.327	0.361	0.374
		Tukey grouping	A	A	A
	Snag	Mean, (g/cm ³)	0.373	0.364	N/A
		Tukey grouping	A	A	N/A
2	Log	Mean, (g/cm ³)	0.270	0.337	0.322
		Tukey grouping	A	A	A
	Snag	Mean, (g/cm ³)	0.374	0.387	N/A
		Tukey grouping	A	A	N/A
3	Log	Mean, (g/cm ³)	0.210	0.270	0.215
		Tukey grouping	A	A	A
4	Log	Mean, (g/cm ³)	0.134	0.145	0.100
		Tukey grouping	A	A	A
5	Log	Mean, (g/cm ³)	N/A	0.099	N/A
		Tukey grouping	N/A	A	N/A

Table 5-21. Comparison of the *Pinus siberica/koraiensis* estimates of mean density among regions for decay class and position

Decay Class	Position	Regions	
		Irkutsk	Khabarovsk
1	Log	Mean, (g/cm ³) Tukey grouping	0.332 A
	Snag	Mean, (g/cm ³) Tukey grouping	0.349 A
2	Log	Mean, (g/cm ³) Tukey grouping	0.332 A
	Snag	Mean, (g/cm ³) Tukey grouping	0.327 A
3	Log	Mean, (g/cm ³) Tukey grouping	0.298 A
	Snag	Mean, (g/cm ³) Tukey grouping	0.316 A
4	Log	Mean, (g/cm ³) Tukey grouping	0.345 A
	Snag	Mean, (g/cm ³) Tukey grouping	0.342 A
5	Log	Mean, (g/cm ³) Tukey grouping	0.227 A
	Snag	Mean, (g/cm ³) Tukey grouping	0.241 A
6	Log	Mean, (g/cm ³) Tukey grouping	0.304 A
	Snag	Mean, (g/cm ³) Tukey grouping	0.333 A
7	Log	Mean, (g/cm ³) Tukey grouping	0.140 A
	Snag	Mean, (g/cm ³) Tukey grouping	0.158 A
8	Log	Mean, (g/cm ³) Tukey grouping	0.104 A
	Snag	Mean, (g/cm ³) Tukey grouping	0.131 A

Table 5-22. Comparison of the *Pinus sylvestris* estimates of mean density among regions for decay class and position

Decay Class		Position	Regions			
			St.-Petersburg	Novosibirsk	Krasnoyarsk	Irkutsk
1	Log	Mean, (g/cm ³)	0.411	0.353	0.351	0.350
		Tukey grouping	A	A	A	A
	Snag	Mean, (g/cm ³)	0.384	0.342	0.355	0.367
		Tukey grouping	A	A	A	A
2	Log	Mean, (g/cm ³)	0.332	0.322	0.340	0.307
		Tukey grouping	A	A	A	A
	Snag	Mean, (g/cm ³)	0.367	N/A	0.362	0.365
		Tukey grouping	A	N/A	A	A
3	Log	Mean, (g/cm ³)	0.240	0.299	0.312	0.262
		Tukey grouping	A	AB	B	AB
	Snag	Mean, (g/cm ³)	0.270	0.375	N/A	0.321
		Tukey grouping	A	A	N/A	A
4	Log	Mean, (g/cm ³)	0.121	0.289	0.179	0.143
		Tukey grouping	A	B	A	A
5	Log	Mean, (g/cm ³)	0.108	0.163	0.114	0.119
		Tukey grouping	A	A	A	A

Table 5-23. Comparison of the *Populus tremula* estimates of mean density among regions for decay class and position

			Regions		
Decay Class		Position	St.-Petersburg	Moskow	Khabarovsk
1	Log	Mean, (g/cm ³)	0.294	0.365	0.354
		Tukey grouping	A	A	A
2	Log	Mean, (g/cm ³)	0.278	0.306	0.256
		Tukey grouping	A	A	A
3	Log	Mean, (g/cm ³)	0.172	0.291	---
		Tukey grouping	A	B	N/A

APPENDIX 6: List of outliers removed from the data set at each level of analysis

6-1. Potential outliers removed from the decay-class specific density data set

Log/snag number	Species	Position	Decay Class	Where collected	When collected	Density
18	<i>Populus tremula</i>	Log	4	Moskow	1999	0.301
18	<i>Larix siberica</i>	Snag	2	Irkutsk	1998	0.688
13	<i>Larix siberica</i>	Log	3	Khabarovsk	1997	0.499
211	<i>Pinus sylvestris</i>	Log	4	Khabarovsk	1996	0.390
525	<i>Betula pendula</i>	Log	3	Novosibirsk	1998	0.444
529	<i>Betula pendula</i>	Log	3	Novosibirsk	1998	0.501
527	<i>Betula pendula</i>	Log	3	Novosibirsk	1998	0.531
539	<i>Betula pendula</i>	Snag	3	Novosibirsk	1998	0.578
531	<i>Betula pendula</i>	Log	4	Novosibirsk	1998	0.462

Table 6-2. Potential outliers removed from the NMS data set ranked by their distance to centroid

Rank	Entity Name	Average Distance	Standard Deviations	Region	Species	CWD Number	Decay Class	Density
1	741	0.90385	4.63837	Moskow	<i>Populus tremula</i>	8	3	0.367
2	296	0.89476	4.51493	Khabarovsk	<i>Larix dahurica</i>	11	3	0.379
3	536	0.8933	4.49508	Krasnoyarsk	<i>Pinus sylvestris</i>	202	3	0.305
4	818	0.88022	4.31739	Novosibirsk	<i>Betula pendula</i>	101	4	0.116
5	520	0.83586	3.71489	Khabarovsk	<i>Quercus mongolica</i>	403	3	0.404
6	537	0.81902	3.48608	Krasnoyarsk	<i>Pinus sylvestris</i>	203	3	0.314
7	292	0.81726	3.4622	Khabarovsk	<i>Larix dahurica</i>	7	3	0.413
8	160	0.8093	3.35409	Irkutsk	<i>Pinus sylvestris</i>	310	3	0.139
9	844	0.80522	3.2987	Novosibirsk	<i>Pinus sylvestris</i>	508	3	0.375

Table 6-3. Potential outliers removed from the decomposition rate-constants data set

Log/snag number	Species	Position	Decomposition time	Where collected	When collected	Density
105	<i>Picea abies</i>	Snag	2	St.-Petersburg	1993	0.174
116	<i>Pinus koraiensis</i>	Snag	8	Khabarovsk	1999	0.204

APPENDIX 7: Structure of the matrices used in multivariate analysis

Table 7-1. Description of the “Qualitative” matrix

Matrix size: 970 pieces x 22 variables

Variable name	Variable type	Variable discription	Variable range	Units
Bcover	Qualitative	Percent bark cover on bole	0-100	%
Needles	Qualitative	Presence/absence of needles/leaves	0 or 1	N/A
Twigs	Qualitative	Presence/absence of twigs	0 or 1	N/A
Branches	Qualitative	Presence/absence of branches	0 or 1	N/A
Barkbr	Qualitative	Presence/absence of bark on branches	0 or 1	N/A
Barkbole	Qualitative	Presence/absence of bark on bole	0 or 1	N/A
Sapsloug	Qualitative	Sapwood sloughing	0 or 1	N/A
Collapse	Qualitative	Log collapsing (unable to support its wght)	0 or 1	N/A
Scatter	Qualitative	Log's cross section is elliptical	0 or 1	N/A
Conks	Qualitative	Presence/absence of conks on bole	0 or 1	N/A
Moss	Qualitative	Presence/absence of moss on bole	0 or 1	N/A
Lichens	Qualitative	Presence/absence of lichens on bole	0 or 1	N/A
Ants	Qualitative	Presence/absence of carpenter ants	0 or 1	N/A
Beetles	Qualitative	Presence/absence of bark beetles/galleries	0 or 1	N/A
Brownrot	Qualitative	Presence/absence of brown rot	0 or 1	N/A
Whiterot	Qualitative	Presence/absence of white rot	0 or 1	N/A
Sapfriab	Qualitative	Sapwood can be crashed by hand	0 or 1	N/A
Hwfriab	Qualitative	Heartwood can be crashed by hand	0 or 1	N/A
Casehard	Qualitative	Log surface is hard while center is soft	0 or 1	N/A
Stubsmov	Qualitative	Branch stubs are moving	0 or 1	N/A
Woodborer	Qualitative	Presence/absence of woodborers/galleries	0 or 1	N/A

Table 7-2. Description of the “Quantitative” matrix

Matrix size: 970 pieces x 5 variables

Variable name	Variable type	Variable discription	Variable range	Units
Bcover	Numeric	Percent bark cover on bole	1-100	%
Age	Numeric	Time span from the date of tree death	1-160	years
Decay	Class	Decay classes	1-5 inclusive	N/A
Density	Numeric	Average density of log/snag	0-1exclusive	g/cm ³
Species	Class	Log/snag tree species	1- <i>Abies siberica</i>	N/A
			2- <i>Betula costata</i>	N/A
			3- <i>Betula pendula</i>	N/A
			4- <i>Pinus siberica/koraiensis</i>	N/A
			5- <i>Larix</i> spp.	N/A
			6- <i>Pinus sylvestris</i>	N/A
			7- <i>Populus tremula</i>	N/A
			8- <i>Quercus</i> spp.	N/A
			9- <i>Picea</i> spp.	N/A