LANDSCAPE PATTERNS AND DYNAMICS IN THE BOREAL FOREST, CENTRAL SIBERIA

Jessica Brooks, University of Arkansas, Fayetteville, AR (*jlno3@cast.uark.edu*)
Mentor: Dr. Don Deering, NASA GSFC, Code 923

***Abstract**. Boreal forests are an integral component of global ecosystems, making up 30% of the world's forested areas and containing 15% of terrestrial carbon. Accordingly, they play a critical role in current climate change projections since they represent such a significant carbon reserve and are located in the region of the world where climate change will have the greatest effects. A fundamental understanding of boreal ecosystems is needed in order to parameterize carbon storage dynamics and predict the reaction of boreal ecosystems to changing conditions. This study, conducted from summer, 2003 to spring, 2004, seeks to use ASTER and ETM+ data in the examination of fundamental biophysical parameters of boreal forests in Central Siberia. In this region, distinctive landscape patterns resulting from the disturbance regime are evident. Landscape patterns and dynamics will be examined in the context of seasonal and regional variation. Data from several field campaigns collected during 1999-2002 will be used for ground verification.*

INTRODUCTION

The boreal zone of the Northern Hemisphere reaches from approximately 45^{o} to 70^{o} N latitude. The forests in this region cover 1.2 billion hectares. This is 30% of all forested areas in the world and 73% of the world's coniferous forests (Conard and Ivanova, 1997). The exploitable component of these forests makes up 47% of the world total export value (Goldammer and Stocks, 2000).

It is generally agreed upon that the boreal forest is a substantial carbon reserve. The carbon stored in this region's ecosystems makes up more than 30% of the total global terrestrial carbon pool. Compared to the temperate and tropical forest complexes, boreal ecosystems contain 20% more carbon than the two combined while comprising only half of the land area (Kasischke, 2000).

Given current circumstances of greenhouse gas-induced global warming, boreal forests are widely recognized as a critical component of world resources (Conard and Ivanova, 1997; Kasischke, 2000; Goldammer and Stocks, 1997). The Kyoto Protocol of the United Nations recognizes the contribution of greenhouse gases to global warming and requires signatory countries to commit to reduction in emissions (Stocks *et al.*, 2000). Accordingly, countries containing boreal forests are increasingly interested in quantifying their carbon budget in order to offset carbon emissions (Kasischke and Stocks, 2000).

High scientific interest in the carbon budget of boreal forests also relates to climate change modeling, a significant component of global change science. Global climate models predict the outcome of climate change and include among their parameters major carbon pools and sources (Houghton, 1996; Kolchugina and Vinson, 1995). The boreal forest carbon budget is a substantial factor of the global carbon budget (Bolin, 1986; Apps *et al.*, 1993; Kolchugina and Vinson, 1993; Bonan, 1991; Kokorin *et al.*, 1996).

Carbon storage

One estimate of carbon storage in boreal ecosystems quoted by Kasischke (2000) is 703 Pg (out of 2100 Pg world total). Carbon stored in boreal soils and peatlands is 625 Pg while 78 Pg is stored in plant biomass. In

1993, Apps and associates estimated the yearly carbon balance of boreal vegetation to be –0.54 Gt C yr^{-1} and of boreal soils to be –0.70 Gt C yr^{-1}, both representing a net carbon sink (Kasischke, 2000).

While boreal ecosystems currently function to sequester carbon, they are predicted to potentially become a net carbon source in the future (Kasischke, 2000; Goldammer and Stocks, 2000; Solomon and Leemans, 1997). Variations in the boreal carbon balance involve major disturbance factors and their interaction with climate change.

BOREAL DISTURBANCE REGIMES

Exploitation

Deforestation inhibits carbon sequestration. As wood shortages become more prevalent, timber in the north once considered unprofitable is now frequently logged, often to sustain fiber supply (for paper and pulp production). Most logging of boreal forests occurs by clear-cutting (Runesson, 2002). Studies have pointed out problems with seedling regeneration in clear-cut stands. Increased deforestation is most likely to occur in Russia, which contains the majority of the world's boreal forest (Kasischke, 2000; Kolchugina and Vinson, 1995).

Oil exploitation is another concern in the boreal region. Oil reserves discovered in Western Siberia are estimated to be comparable to those of Saudi Arabia. Oil fields are a source of hydrocarbons as well as a cause of forest damage. Further, oil and other mineral extraction developments alter hydrology by disturbing permafrost (Ranson *et al.*, 1997). Acidic effluent from tailings contaminates these ecosystems as well (Runesson, 2002).

Pollution

Especially in Russia, pollution impacts the health of boreal ecosystems. Smelters in Noril'sk have caused the world's largest pollution-induced forest decline. The smelters produce SO_2, which have been causing damage in nearby forests since the 1950's. Currently, two million hectares of forest in this region are damaged or dead. Aside from forest damage, underlying permafrost is affected as well. This has implications for hydrology (Ranson *et al.*, 1997).

In addition to SO_2 contamination, many boreal ecosystems have been affected by radioactive waste (Runesson, 2002). Radionuclides contaminate an estimated seven million hectares of the Russian forest. There is great concern about redistribution by fire (FIRESCAN, 1994).

Insects

Insect outbreaks drastically alter boreal forests. Species such as Siberian silkworm (*Dendrolimus sibericus*), Siberian gypsy moth (*Limantria dispar*), and black fir beetle (*Monohamus urussovi*) periodically affect vast amounts of forest. As forest is damaged, decreased canopy density facilitates the growth of grass, which serves as fire ignition material. Additionally, dead, dry trees promote the ignition and propagation of fire (Ranson *et al.*, 1997; Goldammer and Stocks, 2000; Solomon and Leemans, 1997).

Fire

Fire has long been recognized as the primary disturbance factor in boreal forests (Kasischke, Processes Infl., 2000). The FIRESCAN Science Team (1994) lists it as the most important abiotic factor controlling forest structure, species composition, physiognomy, landscape diversity, energy flows, and geochemical cycles of boreal ecosystems. In Russian forests, an estimated 40%-96% of total forested area is in some phase of postfire succession (Shvidenko and Nilsson, 2000).

Fire affects carbon storage in boreal forests in several ways. Most directly, it releases carbon through biomass combustion. This process can be described in terms of fuel consumed as well as combustion characteristics (Bourgeau-Chavez *et al.*, 2000; Kasischke *et al.*, 1995).

There are three major fuel types: crown fuel (foliage and branches in the overstory), fine fuel in ground vegetation and litter (living vegetation and twigs, leaves, and needles), and duff in the ground layer (layers of decomposing litter and decomposed organic soil) (Kasischke *et al.*, 1995; Kolchugina and Vinson, 1995; Conard and Ivanova, 1997). In boreal forests, the ground layer stores the majority of carbon.

Fire consumes biomass through flaming or smoldering combustion. Flaming combustion occurs over short time periods in localized areas. It typically occurs in the crown and fine fuel (surface) layers. Smoldering, or glowing, combustion can last long after flaming combustion has occurred. It typically consumes ground layer fuels. Crown and surface fires usually occur in conjunction with smoldering ground fires (Kasischke *et al.*, 1995).

Fire further affects carbon storage in boreal forests by changing the pattern of secondary succession (Kasischke *et al.*, 1995; Campbell and Flannigan, 2000; Shvidenko and Nilsson, 2000). For a combination of reasons, forest fires change vegetation characteristics. Fire opens space in the crown, allowing shade intolerant young growth (aspen and birch) to flourish (Kolchugina and Vinson, 1995). It additionally affects succession by altering the ground layer. Ground fire often consumes the thick layers of organic soil found in boreal forests, exposing mineral soil below. Certain species are adapted to successful germination in exposed mineral soil. Moreover, certain species are physically adapted to fire survival. These species usually dominate after a fire. Hence, a typical postfire successional pattern can be identified in many cases (Bourgeau-Chavez *et al.*, 2000). Plant composition during succession influences rates of biomass/atmosphere carbon exchange (Kasischke, Processes Influ., 2000; Kasischke *et al.*, 1995).

As previously mentioned, the organic ground layer contains the majority of carbon in boreal ecosystems. Fire changes the amount of carbon stored in this layer by significantly altering its thermal and moisture regimes, which control plant succession, photosynthesis, and soil microbial processes. As soil temperature and moisture is altered, so are rates of decomposition (and carbon storage) (Kasischke *et al.*, 1995). Undisturbed soil in the boreal region experiences little decomposition and accumulates a thick organic layer due to low soil temperatures and poor drainage. However, soil typically becomes warmer and drier after a fire, resulting in increased decomposition. Postfire soil temperature increases are caused by reduction of albedo/increased solar radiation and loss of the insulating ground layer (vegetation, litter, organic soil). These conditions result in net carbon emission from the ground layer for several years after fire (Kasischke, 2000; Kasischke, Processes Influ., 2000; Kasischke *et al.*, 1995).

A fourth component of the relationship between fire and carbon storage involves nutrient release. In the absence of regular decomposition, organic material builds up on the forest floor, tying up nutrients available for biological rotation. This process gradually leads to a decrease in forest productivity (Sheshukov, 1996; Bourgeau-Chavez, 2000). Fire releases vital nutrients through combustion of biomass and increased decomposition of organic matter. Although these processes represent an immediate loss of carbon, some carbon is eventually regained through increased plant productivity (Kasischke *et al.*, 1995).

Finally, fire frequency influences carbon storage of boreal forests by determining stand age distribution. Although vegetation productivity following a fire can be high, the total amount of biomass is much smaller (storing less carbon) than an older stand. The level of biomass (in all forest layers) in a stand increases with age, and so a stand that burns less frequently will sequester more carbon than one that burns more frequently (Kasischke *et al.*, 1995; Kasischke, 2000).

Researchers often describe the typical activity and patterns of fire- the fire regime- of an area. Four elements make up the fire regime: fire intensity, interval, season, and size. Fire intensity varies with amount and type of fuel consumed. Fire interval is the average number of years between fire occurrences at a certain location. Fire season refers to the time of year of the fire and is important since it influences plant phenology. Fuel availability and type, moisture, lightening incidence, physiography, and climate can all affect the fire regime (Campbell and Flannigan, 2000; Bourgeau-Chavez *et al.*, 2000).

CLIMATE CHANGE

The foremost cause of carbon emissions from boreal ecosystems involves climate change. There is a general consensus within the scientific community that anthropogenic global warming is occurring. With a doubling of CO^2 and other greenhouse gases in the atmosphere, global climate models predict an average $1^o – 3^oC$ rise in air temperature within the next fifty years (Kasischke *et al.*, 1995).

Most GCMs project the greatest temperature changes to be in the northern latitudes. The Canadian Climate Center Global Climate Model (CCC GCM) projects 4^o-12^o warming in the winter and 2^o-6^o warming in the summer in the north. This estimate is consistent with the predictions of other GCMs. Increases in precipitation are not expected to occur in conjunction with these temperature increases, resulting in warmer, drier conditions (Kasischke *et al.*, 1995; Conard and Ivanova, 1997).

Climate change can alter all aspects of boreal ecosystems. Carbon storage in the biomass and ground components is altered, and ecosystem distributions shift. Eventually, a new equilibrium is established.

Influence on living biomass

Several studies have estimated the change in carbon storage of living biomass given current climate change projections. Shifting forest distributions significantly affects carbon storage (Solomon and Leemans, 1997). Smith et al. (1992) estimate that only 28% of the world's current boreal forests will remain intact in the future. Instead, the current boreal region will be populated with temperate, mixed-deciduous forests. These forests are known to sequester more carbon than boreal forests. Based on an estimate by Kolchugina and Vinson, Kasischke et al. (1995) say this shift represents an eventual one-third increase in total carbon stored in living biomass in the boreal region.

Climate-related changes in fire regimes will also significantly impact living biomass carbon storage (Goldammer and Stocks, 2000). A rise in air temperature coupled with soil moisture reduction (due to static precipitation levels) will cause increased occurrence of extreme droughts and optimum fire conditions (FIRESCAN, 1994; Stocks *et al.*, 2000; Campbell and Flannigan, 2000). Moreover, the typically short fire season would be lengthened, causing an increase in annual area burned (and a shorter fire return interval) (Conard and Ivanova, 1997). The fire return interval influences stand age distribution and hence carbon storage. Increased fire frequencies represent carbon loss from direct combustion and younger stands (Kasischke *et al.*, 1995).

Ecosystem flammability is another fire-related factor influenced by climate change. In the long term, climate change will cause a decrease in living biomass flammability. This is due to the vegetation shift to deciduous trees (Kaischke *et al.*, 1995). Regarding living biomass, predicted climate changes are expected to cause a net increase in carbon storage. The shift of vegetation to deciduous species is the dominant factor here (Kasischke *et al.*, 1995).

Influence on ground layers

The climate-induced net increase in living biomass carbon storage is offset by a net decrease in carbon storage of ground layers. As air temperature rises, soil becomes warmer and drier. Under these conditions, the active layer (thawed permafrost) deepens, and decomposition increases. This process releases carbon stored in organic soils (Kasischke *et al.*, 1995).

The changes in fire regime discussed previously also act to release carbon from ground layers. Shorter fire return intervals facilitate carbon release through ground fires and warmer postfire soil conditions. Moreover, the reduction in soil moisture causes an escalation in ecosystem flammability. This change is more immediate than the reduction in flammability caused by vegetation shift (Kasischke *et al.*, 1995).

Net effects of climate change

Kasischke and associates (1995) quantified all of these factors in order to generate climate change-related carbon storage estimates for boreal ecosystems. According to their study, given a 50% increase in the annual area burned, there will be a net carbon loss of 0.5-0.8 Pg/yr over the next 50-100 years. This represents an estimated loss of 25-80 Pg of carbon in the near term. This estimate takes into account the time lag between immediate carbon loss from increased fire frequency and ground conditions and eventual carbon gain from the vegetation shift. After approximately 175 years, the net carbon loss would decrease as the boreal system shifts.

Smith et al. (1992) project a shift of current tundra and peatland ecosystems to boreal forest. Though fire is not a dominant factor in these ecosystems, it is a dominant factor in forests. If fire began to affect these newly forested areas, the large carbon pool in this region could be disturbed. Together, the three ecosystems mentioned here contain more than 40% of carbon stored in terrestrial ecosystems (mostly in the ground layer) (Kasischke *et al.*, 1995).

It is important to note that a climate change-induced increase in boreal carbon emissions would form a temporary feedback loop to global warming. This process would likely be limited to a transition period until a new climate-ecosystem equilibrium is established (FIRESCAN, 1994; Goldammer and Furyaev, 1996).

RUSSIAN BOREAL FOREST

Russia contains two thirds of the world's boreal forests (Conard and Ivanova, 1997). Estimates of carbon storage in Russian boreal ecosystems range from 119 to 323 Pg (Alexeyev *et al.*, 1995; Dixon *et al.*, 1994). For political reasons this region was excluded from international scientific study until the early 1990's. Due to the relatively poor scientific record in this area and the relationship between boreal forests and climate change, scientific interest in Russian boreal ecosystems is high (FIRESCAN, 1994; Krankina and Dixon, 1994).

Scientific Initiatives

Starting in the 1990's, several international research initiatives have facilitated the scientific study of Russian boreal ecosystems. Some of the largest include the International Geosphere-Biosphere Program (IGBP), the International Global Atmospheric Chemistry Project (IGAC), the International Boreal

Forest Research Association (IBFRA), the Fire Research Campaign Asia-North (FIRESCAN), and the Northern Eurasia Earth Science Partnership Initiative (NEESPI) (Goldammer and Furayev, 1996).

Research

Large-scale research projects funded by one or more of the programs listed previously have provided a base for current scientific study. One example of these is the Bor Forest Island Fire Experiment, conducted in 1993 in Krasnoyarsk Kray, Russia. This project involved a large controlled, experimental burn of a boreal forest stand conducted in order to measure several fire-associated parameters. Such parameters include fire emissions, pre- and post-fire soil conditions, post-fire succession, and tree mortality (FIRESCAN, 1994).

Technological advances in the field of remote sensing have facilitated the use of satellites in studies of boreal ecosystems. Currently, remote sensing is commonly used in the following applications: obtaining Leaf Area Index (LAI), mapping the size, extent, and severity of fire, estimating stand composition and age, determining post-fire mortality, estimating fire return interval, and examining canopy characteristics. The majority of remote sensing work done in boreal forests involves fire mapping.

Current Study

The current study, begun in summer 2003, involves the synthesis of remote sensing and ground-collected data in order to examine some fundamental biophysical parameters of boreal forests in Krasnoyarsk Kray, Central Siberia. Field data were collected at several sites in Krasnoyarsk from 1999-2002. Field data include such parameters as stand age, post-fire stand age, exposition and slope, species composition, stocking density, height, crown density, and post-fire mortality. These data will be used in conjunction with Landsat Enhanced Thematic Mapper (ETM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data.

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