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Road Network Optimization Model for Supplying Woody Biomass Feedstock for Energy Production in Northwestern Ontario

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Abstract: The road network optimization problem is one of the most difficult and challenging problems in transport planning. Most of the research in this area has focused on finding an optimal solution in order to minimize the total travel cost in the network with given demand from each origin to each destination, while accounting for different route characteristics in the network. In this paper, we develop a raster-based road network optimization model to assist in woody biomass procurement decision-making for bioenergy production in northwestern Ontario. We incorporate speed and load constraints on different types of roads and seek minimum time and cost (or shortest distance) from any grid cell (1 km x 1 km) to any road containing cell in an area covering 167,184 km^2. We also determine the minimum raster resolution that supplies consistent results at local and regional scales. Finally, we establish variable cost zones surrounding four northwestern Ontario power generating stations using woody biomass feedstock. Although, the network optimization model has been developed for supplying woody biomass feedstock to the power generating stations, it can be used for transporting any material across the region.

Keywords: Bioenergy, minimum time, northwestern ontario, road network, transportation planning, woody biomass.

INTRODUCTION

The road network optimization problem involves an optimal decision on the choice of route in response to the given demand for transporting material from each source to each destination. It has emerged as an important area for research in handling effective transport planning, because the demand for transportation of material on the roads is growing, while resources available for expanding the system capacity remain limited. Optimized transport over the road network plays a vital role in bioenergy production, as woody biomass is bulky and of low value. Thus, transportation and logistics play a vital role for making emerging biomass-based renewable energy businesses efficient and profitable [1, 2]. The increased cost of non-renewable fossil energy and its effect on climate change through greenhouse gas (GHG) emissions has led to some cutting-edge research in renewable bioenergy production systems [3,4]. However, there is little research focused on formulation and solution procedures in woody biomass supply chain optimization for power generation.

The mathematical models and algorithms developed for biomass transportation focus either on cost calculation or optimal location of bioenergy power plants. For example, Singh *et al.* [5] developed a mathematical model for collecting and transporting agricultural biomass feedstock from agricultural fields to a biomass-based power plant in Punjab, India. They compared the unit cost of biomass transportation for two modes of transport (truck and tractor with wagon) and three types of agricultural biomass (loose biomass, baled biomass and briquetted biomass). Velazquez-Marti and Fernandez-Gonzalez [6] formulated a mathematical algorithm to optimally locate biomass-based power plants in Spain by minimizing transportation costs, under the constraint that all the bioenergy produced by the biomass-based power plant is used. They used the mathematical model to select power plant location points on the map that minimize transportation cost under the given constraints.

Transportation models for efficient and effective biomass supply logistics for bioenergy production face a number of other challenges in model formulations [4]. A crucial decision of the road network optimization problem is the full capacity utilization of existing roads (primary and secondary) and/or the addition of new links (tertiary forest roads). Such a decision is referred to as the network design problem, which determines the optimal decision variables (e.g. full capacity utilization and/or new link additions) so as to minimize a specific network performance index (e.g. total travel time or generalized cost), while accounting for different route characteristics in the network. The generalized cost of energy recovery from woody biomass mainly depends on the logistics cost of supplying biomass feedstock to the power plants [1, 7, 8]. Using four different feedstocks (forest fuel, straw, miscanthus and short rotation coppice), Allen *et al.* [9] found that biomass logistics costs (transport, storage and handling) constitute a significant part of the total costs of the biomass supply chain. In addition Nichols *et al.* [10], in their study on provincial road conditions and round wood timber transport in South Africa, found that road type and conditions also have a substantial effect on transportation costs.

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Spatial data analysis techniques are often used to find shortest distance in road network problems. Geographic Information Systems (GIS) have been used to compile, clean and analyze all types of spatial data and to build raster spatial databases of road networks for supplying woody biomass for energy production [11-13]. In raster format, the geographic location of each cell is determined by a single attribute, its position relative to the point of origin (bottom left corner) of the cell matrix, and no other geographic coordinates are required to be stored [12, 14, 15]. This technique of data storage in raster format makes the data analysis much easier in network optimization models and has allowed the development of efficient solution techniques for solving very large cyclic network problems [16, 17]. The raster format is also better than the vector format, as it works even in areas where predefined paths do not exist and many attribute layers are not required [15].

Hawth's Tools [18] are further used in ArcGIS to analyze spatial data [12, 19]. The sources and destinations of the network are identified in a GIS based system for biomass logistics and transport optimization [6, 20]. The nodes of network structure as biomass sources, storage locations or biomass-based power plants are connected through arcs in the network. The combination of ArcGIS and Visual Basic has been applied for spatial road network analysis [12, 13, 19, 21, 22]. Kanzian *et al.* [23] performed scenario analyses for regional energy wood logistics for optimizing fuel supply by combining GIS and linear programming. Geijzendorffer *et al.* [24] used a combination of GIS-BIOLOCO tools for designing and assessing the effectiveness of biomass delivery chains at regional levels based on biomass availability, logistics, costs, and spatial and environmental conditions. Further, several database layers for roads can be developed in ArcGIS, using a precedence/absence type of data input method [25]. These database layers help in finding the minimum time (or shortest distance) in road network models and establishing variable cost zones around power generating plants.

There are three existing woody biomass consuming power generating plants, plus one coal plant currently being converted, in northwestern Ontario (NWO) west of Lake Nipigon. The general purpose of this research is to build a road network optimization model to assist in planning woody biomass transportation and logistics for bioenergy production at a minimum cost in a sustainable way. The specific objectives of this study are: (i) to develop a minimum time and cost (or shortest distance) road network model to transport woody biomass feedstock to the power generating stations; (ii) to determine the minimum raster resolution that supplies consistent results at a regional scale; and (iii) to establish variable cost zones surrounding the power generating plants in NWO.

METHODS

Research Area

The research area for this study (Fig. **1**) consists of 18 Forest Management Units (FMUs) in NWO covering an area of 167,184 km^2 (324 km x 516 km). Twelve FMUs (Armstrong Forest, Black Sturgeon Forest, Crossroute Forest, Dog-River Matawin Forest, Dryden Forest, English River Forest, Kenora Forest, Lakehead Forest, Sapawe Forest, Spruce River Forest, Wabigoon Forest, and Whiskey Jack Forest) are completely within the research area, whereas six FMUs (Caribou Forest, Lac Seul Forest, Lake Nipigon Forest, Ogoki Forest, Red Lake Forest, and Trout Lake Forest) are partially within the research area. Woody biomass from these FMUs will be supplied to four biomass-based power plant developments (Abitibi-Bowater, recently renamed as Resolute Forest Products, Thunder Bay Power Plant (ABTB); Abitibi-Bowater Fort Frances Power Plant (ABFF); Atikokan Generating Station (AGS); Domtar Dryden Power Plant (DDPP)) (Fig. **1**). ABTB, ABFF and DDPP are combined heat and power (CHP) generating plants and AGS is only a power (electricity) generating plant.

Data Source

Two types of data (field inventory and GIS) were used for this study. Field inventory data on woody biomass availability from two FMUs – one in the eastern part (Black Sturgeon Forest) and another in the western part (Crossroute Forest) of the research area – were collected. The pre- and post-harvest field inventory data of two FMUs (Black Sturgeon Forest and Crossroute Forest) were only used for assessing the amount of woody biomass (both forest harvest residue and underutilized wood) available in the area. The details of pre- and post-harvest field inventory data collection and their results are available in Alam and Pulkki [32] and Alam *et al.* [35]. The amounts of biomass available in the two FMUs were then related to the forest depletion layer and productive forest layer of these FMUs. Since there were no significant differences, the results of the studies were then integrated with the GIS data (forest depletion layer and productive forest layer) from 18 FMUs to assess the amount of biomass available per square km in each of the 18 FMUs. GIS data were obtained for the road network in two formats (Shapefile and Geodatabase). Road network data of some FMUs (Crossroute Forest, Dog River Matawin Forest, Dryden Forest, English River Forest, Kenora Forest, Lac Seul Forest, Red Lake Forest, Sapawe Forest, Trout Lake Forest, Wabigoon Forest, and Whiskey Jack Forest) were available in a projected coordinate system of NAD 1983 UTM Zone 15N, and for some FMUs (Armstrong Forest, Black Sturgeon Forest, Caribou Forest, Lake Nipigon Forest, Lakehead Forest, Ogoki Forest, and Spruce River Forest) in a projected coordinate system of NAD 1983 UTM Zone 16N. The whole database was converted to a coordinate system of NAD 1983 UTM Zone 15N for uniformity before further analysis. The road network data of the Black Sturgeon Forest, Crossroute Forest, Dog River Matawin Forest, English River Forest and Spruce River Forest were provided by Abitibi-Bowater Inc., Thunder Bay [26]; road network data of the Sapawe Forest were provided by GreenForest Management Inc., Thunder Bay [27]; whereas road network data of the Lakehead Forest were provided by Greenmantle Forest Inc., Thunder Bay [28]. The road network data for rest of the FMUs were collected from Land Information Ontario [29] and OMNR [30].

Data Input and Analysis

The flow chart in Fig. (**2**) shows details of data input and analysis for GIS and aspatial data used for this study. The

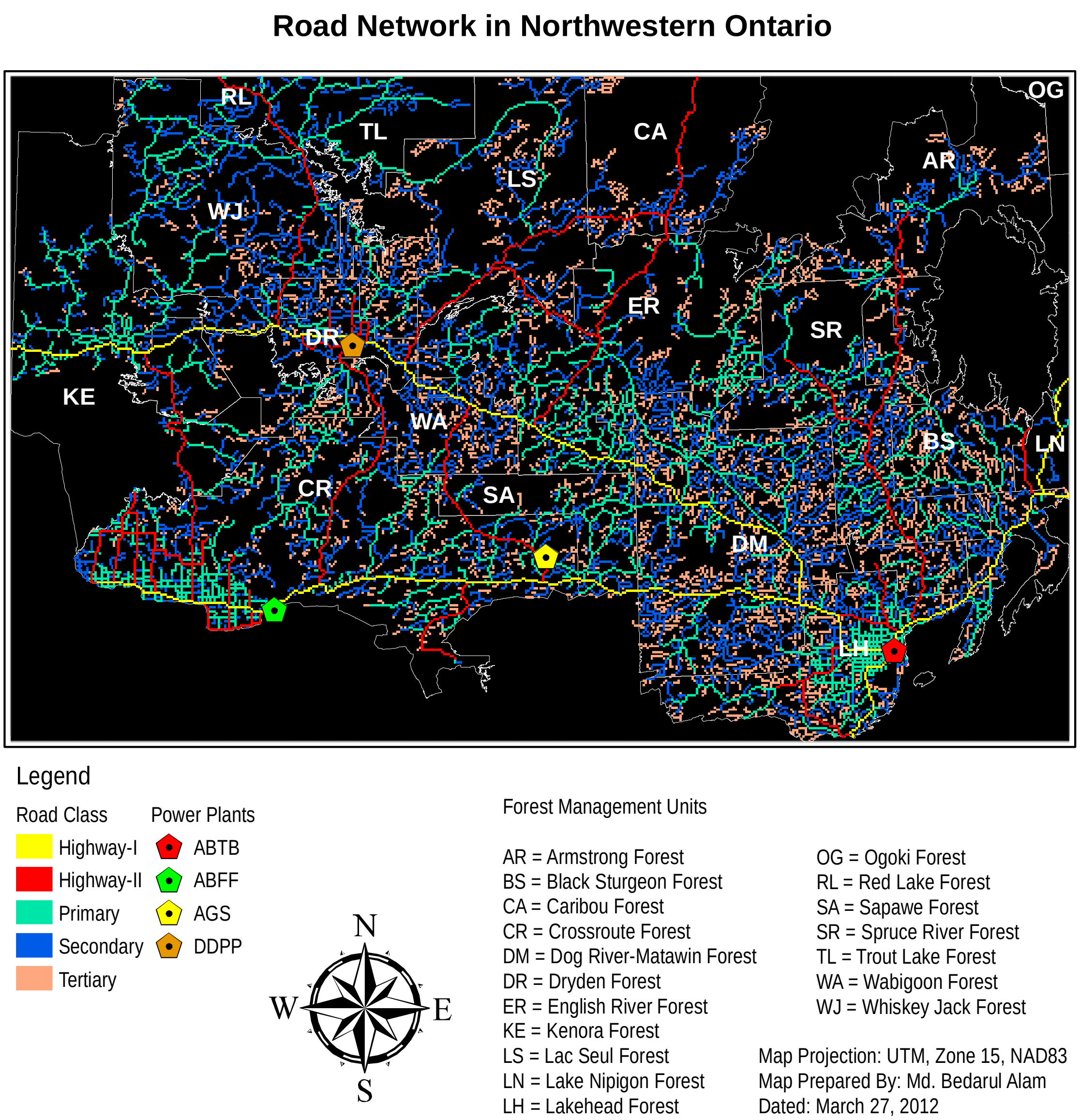


Fig. (1). Road network in research area for the extent of 324 km (N-S) x 516 km (E-W) in northwestern Ontario (NWO).

GIS shapefile and geodatabase for the road network are in vector format. ArcGIS was used to convert these databases from vector format into an easily workable database for this study [12, 13]. These vector road network data were first converted into raster format of 1 km^2 (1 km x 1km) grid cells. The size of raster cells depends on the resolution requirements. A raster cell could be smaller than 1 km^2 (e.g. 100 m^2, 1 m^2), however, smaller cell size requires a large number of cells and a much greater time to process the information [31].

The raster grids were transformed to ASCII (.txt) files, with each cell representing a feature. A grid code could be easily assigned to a cell, if it contains only one type of feature [31]. However, the decision making to assign a grid code to the cell becomes difficult when only a small portion of the cell contains a particular feature [11, 32, 33]. Therefore, different data input methods were used for different types of features [25]. For example, grid codes were assigned to the cells for road layer data input using the presence/absence method [12, 13] and the grid codes 1, 2, 3, 4 and 5 represent highway-I, highway-II, and primary, secondary and tertiary (operational) forest roads, respectively. If no roads were present, grid code 9 was assigned to the cell (Fig. **1**).

The roads passing within a distance of 1 km touch each other in the grid layer. This creates a link in the road network, though in reality there is no link. The coding of grid cells was adjusted manually to eliminate links, which

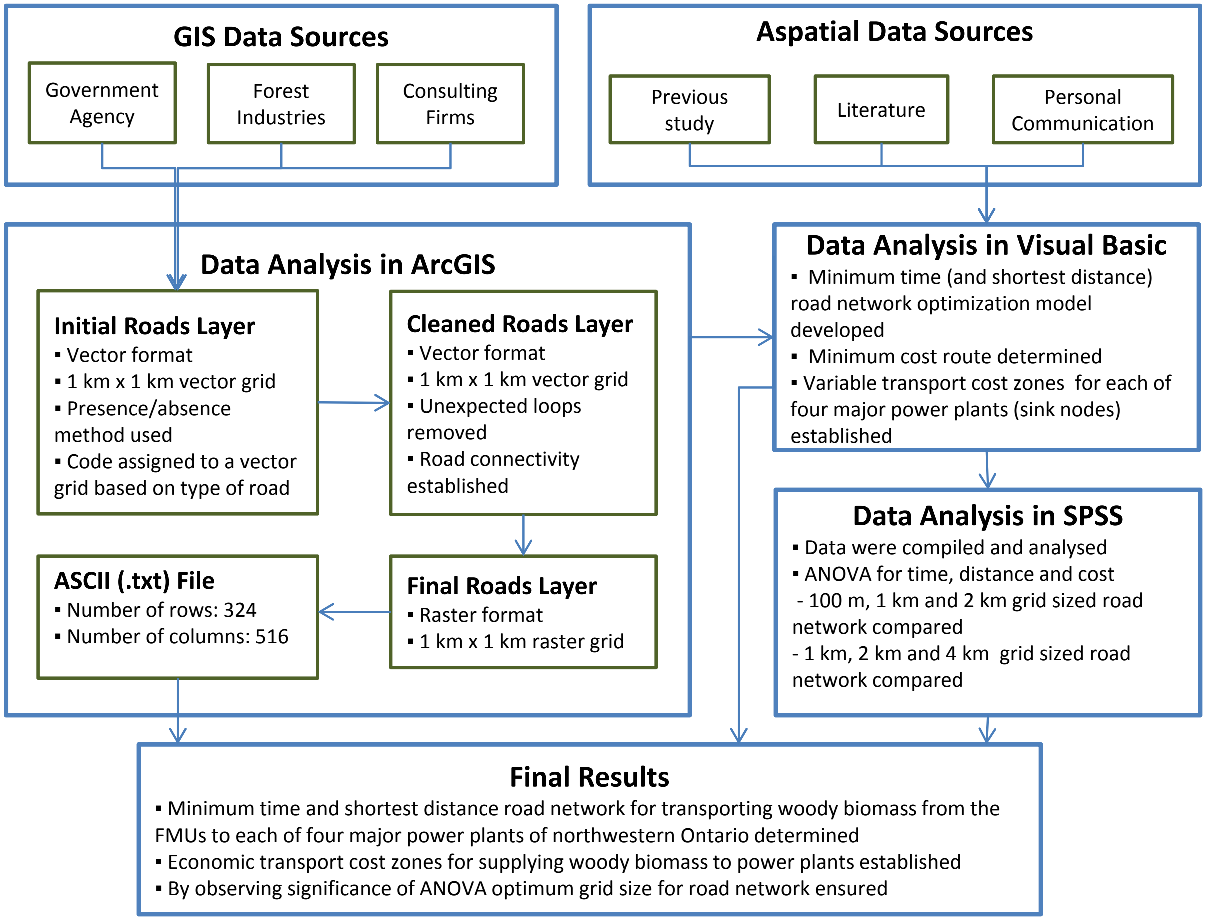


Fig. (2). Flow chart of GIS-based road network optimization model.

were not present on the ground [32]. However, deviations in the network were kept to a minimum during manual adjustment of the road network. In the road network, a higher-class road could touch a lower-class road on more than one side. But a lower-class road could not touch the higher-class road on more than one side. This is necessary to prevent the algorithm from jumping to the higher class road prematurely. When a lower-class road touched a higher-class road on more than one side, the grid cells were adjusted so that the lower class road touched higher class roads only from one side [25]. Fig. (**3**) shows the incorrect road intersection between two different classes of roads in which a lower-class road (secondary road) touches a higher-class road (primary road) on both sides. Fig. (**4**) shows the correct road intersection between two different classes of roads in which a lower-class road (secondary road) touches a higher-class road (primary road) on one side only [25, 32].

The ASCII (.txt) files along with aspatial data were analyzed using a raster-based road network optimization model programmed in Visual Basic that minimizes time and cost (or shortest distance) for transporting woody biomass for energy production in NWO. Driving speeds of 90, 80, 60, 40 and 30 kilometres per hour ($km \cdot h^{-1}$) for empty vehicles, and 90, 70, 50, 30 and 20 ($km \cdot h^{-1}$) for loaded vehicles were used for highway-I, highway-II, and primary, secondary and tertiary (operational) forest roads, respectively. A load size of 50 m^3 for a woody biomass truck with 53 foot trailer with belly, which is equivalent to 43.8 green tonnes (gt) (1 m^3 = 0.876 gt), and an hourly rate of $85 (2009) for a biomass truck (with operator) were used in the model. In addition, a fixed time of 2.5 hours per trip for loading, unloading and delay was used. The previously developed raster layer of productive forests for the 18 FMUs [32, 35] is integrated with the road network layer to determine the minimum transportation cost of woody biomass from each forest cell to each of the four power plants (ABTB, ABFF, AGS and DDPP). Analysis of variance was used to determine the minimum raster resolution that supplies consistent results at a regional scale. Finally, variable cost zones for transporting woody biomass for energy production for each of the power generating plants were established.

Road Network Minimization Algorithm

The road network minimization algorithm was developed by incrementally determining cost between source node and all other nodes[1]. The cost from each source node to all other nodes were repeatedly compared and the least time and cost (or shortest distance) option was determined. The model then proceeds to the next node until the destination is reached. The road network minimization algorithm is a cyclic

[1]The minimization algorithm technique is based on details described in [16, 17, 34].

network because the loops are created by two-way traffic. If an arc is one-way the distance in the closed direction is set to infinity.

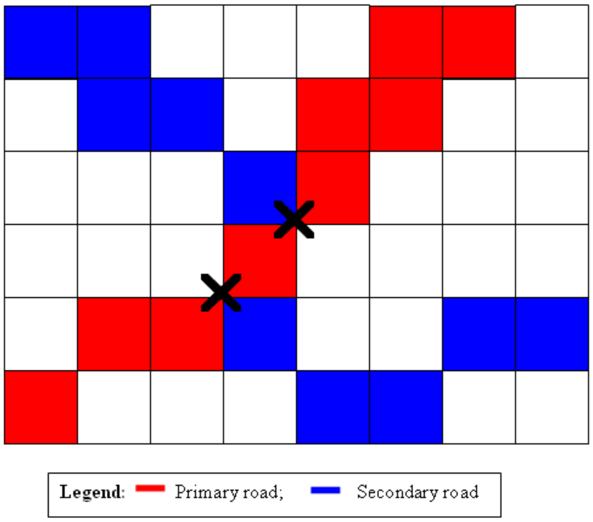


Fig. (3). Incorrect road intersection between two different classes of roads [25, 32].

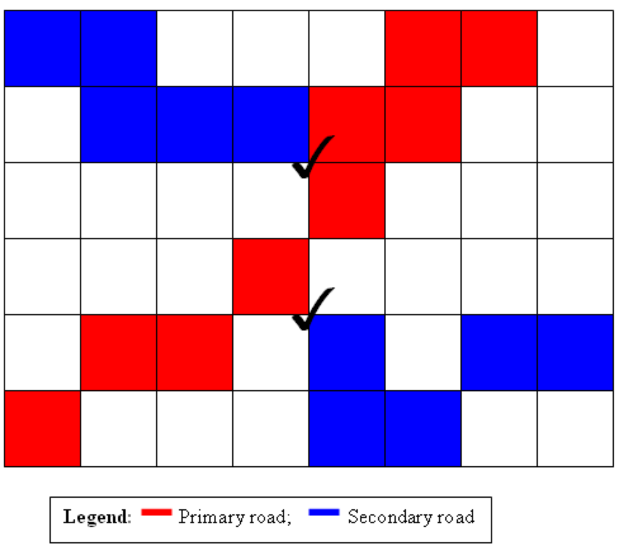


Fig. (4). Correct road intersection between two different classes of roads [25, 32].

Let u_i denote the summation of time or cost (or distance) from node i to all other closest n nodes, and v_j the summation of time or cost (or distance) from all closest n nodes to the node j. The closest nodes refer to the eight adjacent nodes surrounding any node i. However, once we move from one node to another node, the summation is done over all n nodes (finally selected in each step) enroute from source node to the final destination node. The steps of the algorithm are described as follows:

Step 1: Initial Solution

- For start node (i=j=1) set $u_i = v_j = 0$;
- Provided an arc exists between any two nodes i and j, the value of $v_j = \min(u_i + d_{i,j})$ is computed, where $d_{i,j}$ is the time or cost (or distance) between nodes i and j;
- The value of v_j obtained in the previous step is retained and u_i is set equal to v_j for further computation in the network.

Step 2: Optimality Check

a Compute v_j-u_i for all j and i =1;

b If $d_{i,j} \geq v_j$-u_i for all j, then no shorter route can be found between i and j; otherwise set i = i + 1 and repeat sub-step (a) till i = n (last node). When i = n, go to Step 3;

c If $d_{i,j} < v_j - u_i$, compute and replace v_j with a new value, $v_j' = u_i + d_{i,j}$ and start afresh from sub-step (a)

Step 3: Least Time or Cost (or Shortest Distance) Path Determination

The values of v_j, obtained in Step 2, give the least time or cost (or shortest distance) from any node i to j in the network. In order to determine the least time or cost (or shortest distance) path in the network, the last arc (n-1, n) of the chain must satisfy $u_{n-1} = v_n - d_{n-1,\,n}$ and the penultimate node n-2 must satisfy $u_{n-2} = v_{n-1} - d_{n-2,\,n-1}$. The process is repeated backwards (by repeatedly setting n = n-1), until node 1 in the minimum time or cost (or shortest distance) network is reached.

Calculating Transportation Distance, Time and Cost through Road Network

Transportation Distance

There are 26,405 cells (1 km^2 each) containing a road in the research area of 167,184 km^2 (167,184 total cells). The transportation distance for carrying woody biomass per trip from a road cell (source node) to a power plant (sink node) through the road network is determined by Equation (1).

$$D_r = \sum_{t=1}^{5} R_{rt} \tag{1}$$

where,

r = road cells in the raster route (r = 1, 2, 3,…, 26405)

t = types of roads (t = 1, 2, 3, 4, 5)

R_{rt} = distance between nodes

D_r = Transportation distance from the source node to sink node (distance is taken as 1 km if the route is along the cell wall and 1.4142 km if the route is along the cell diagonal).

Transportation Time

Woody biomass transportation time per trip from a road cell (source node) to a power plant (sink node) through the road network is determined by Equation (2).

$$T_r = \frac{D_r}{\sum_{t=1}^{5} S_{ert}} + \frac{D_r}{\sum_{t=1}^{5} S_{lrt}} \tag{2}$$

where,

T_r= Woody biomass transportation time (hours) from a road cell (source node) to power plant (sink node) through road network

S_e = speed ($km \cdot h^{-1}$) of empty vehicle

S_l= speed ($km \cdot h^{-1}$) of loaded vehicle.

Transportation Cost

The transportation cost of woody biomass per trip from a road cell (source node) to a power plant (sink node) through the road network is determined by Equation (3).

$$TC_r = VC_r + FC \tag{3}$$

where,

TC_r = transportation cost ($\$ \cdot gt^{-1}$) to transport woody biomass from a road cell (source node) to power plant (sink node) through the road network

VC_r = variable transportation cost ($\$ \cdot gt^{-1}$) obtained from Equation (4)

$$VC_r = \frac{T_r \times P}{L \times f} \tag{4}$$

where,

FC = fixed transportation cost ($\$ \cdot gt^{-1}$) obtained from Equation (5)

$$FC = \frac{FT \times P}{L \times f} \tag{5}$$

where,

P = payment rate ($\$ \cdot h^{-1}$) for truck including operator (assumed = 85 $\$ \cdot h^{-1}$)

L = load size (m^3) of wood biomass truck (assumed = 50 m^3)

f = Conversion factor for biomass from cubic metre to green tonne (1 m^3 = 0.876 gt)

FT = fixed time (h) for loading, unloading and delay per trip (assumed = 2.5 h).

Determining Minimum Raster Resolution

In order to determine the minimum raster resolution that supplies consistent results at both local and regional scales with reasonable road layer preparation and processing times, analysis of variance was conducted for trip distance and time results for a 50 km x 50 km raster (local) for five road network locations and three grid sizes (100 m x 100 m, 1 km x 1 km and 2 km x 2 km) (Fig. **5a**). Then analysis of variance was also conducted for a larger raster (160 km x 240 km) (regional) for five road networks and three grid sizes (1 km x 1 km, 2 km x 2 km and 4 km x 4 km) (Fig. **5b**).

Variable Cost Zones

The transportation costs of woody biomass through the road network from source nodes to each sink node (power plant) were classified into variable transportation cost zones using integer codes (1, 2, 3, 4, 5 and 6 for variable transportation costs of 0-5, 5-10, 10-15, 15-20, 20-25 and 25-30 $\$ \cdot gt^{-1}$, respectively). The variable transportation costs were developed for each power plant (ATTB, ABFF, AGS and DDPP).

Application of Road Network Model to Transport Woody Biomass

The road network model was integrated with the productive forest layer and depletion forest layer (grid cell with harvesting from 0% to 100% of its area) to determine time and cost of woody biomass transport from the entire productive forest area, as well as just from the cells with harvesting activities over the period 2002-2009, to any sink node (power plant). There are 100,061 cells (out of 167,184 cells) in productive forests and 19,315 forest cells in the harvested forest layers within the research area [32, 35]. The structures of the map layers (productive forest layer and forest depletion layer) are quantitative and indicate the amount of biomass (both types) available in each cell (1 km^2).

Not all productive forest or depletion cells are adjacent to a road cell. Therefore, in the model an offset value of 50 km was used to search for the nearest least cost road cell. A winding coefficient along with reduced loaded and unloaded driving speeds were applied to the straight line distance from the non-adjacent supply cell to the nearest least cost road cell to get the additional time required to move to the road. The minimum access time from the forest cells to the nearest road node is determined by Eq. (6).

$$T_a = \frac{\sqrt{W((RN_v - RN_1)^2 + (CN_h - CN_1)^2)}}{S_1} + \frac{\sqrt{W((RN_v - RN_1)^2 + (CN_h - CN_1)^2)}}{S_2} \tag{6}$$

where,

T_a = Access time from the road cell r to forest cell m (hours)

W = winding coefficient applied to straight line distance (assumed = 1.38)

RN_v = row number of forest cell (v = 1, 2, 3, ..., 324)

RN_1 = row number of forest cell at road cell r

CN_h = column number of forest cell (h = 1, 2, 3, ..., 516)

CN_1 = column number of forest cell at road cell r

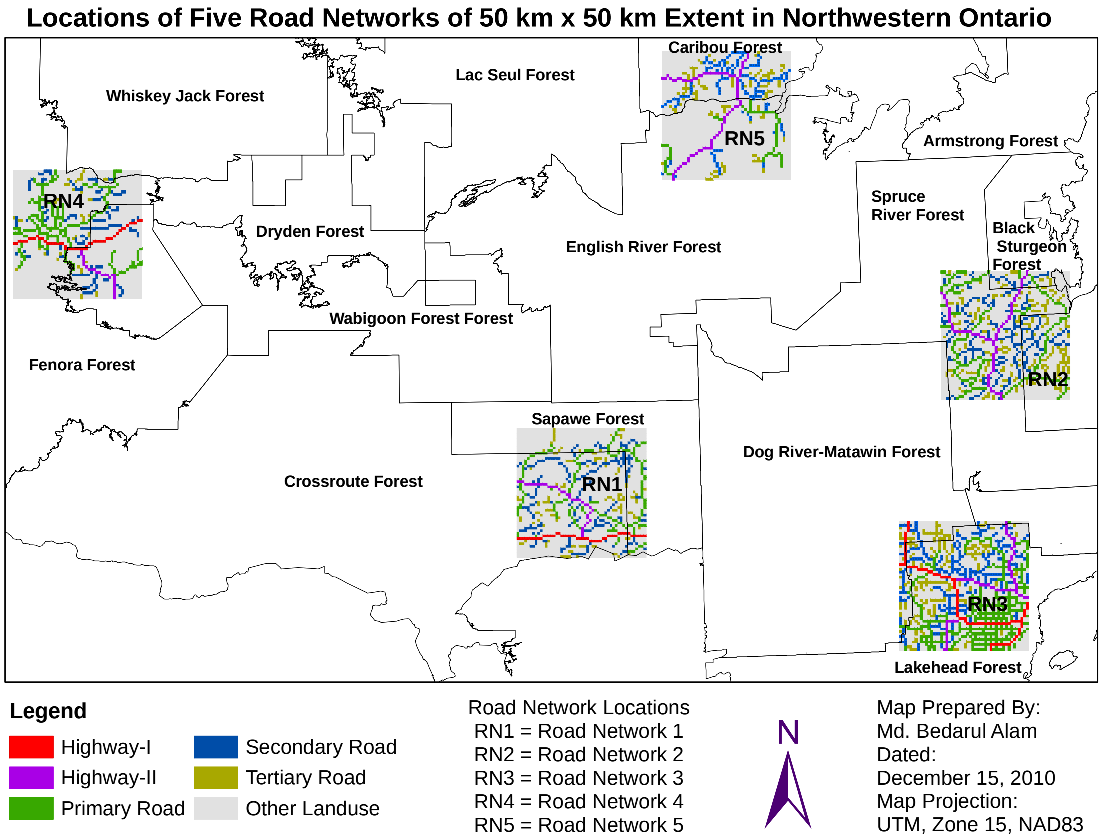
S_1 = speed of empty vehicle from road to forest (assumed = 20 $km \cdot h^{-1}$)

S_2 = speed of loaded vehicle from forest to road (assumed = 10 $km \cdot h^{-1}$)

The transportation time of woody biomass per trip from a forest cell (source node) to a power plant (sink node) can be determined by Equation (7).

$$T_c = T_r + T_a \tag{7}$$

(**a**)



(**b**)

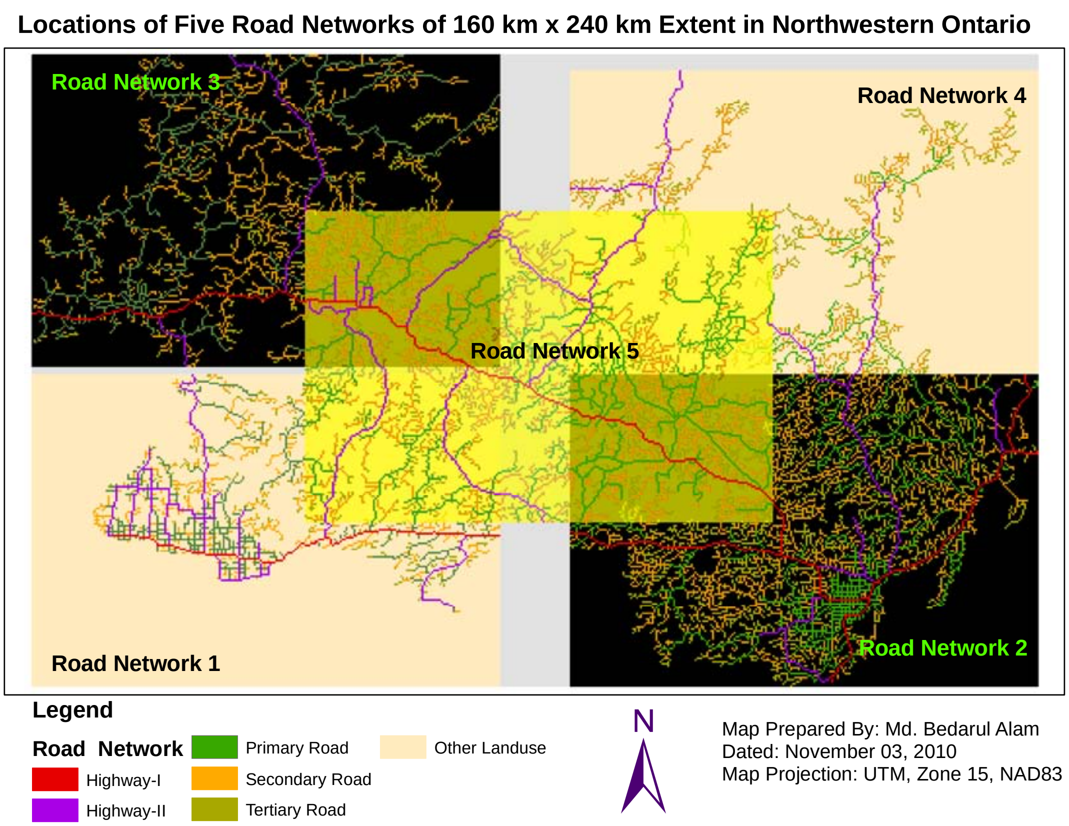


Fig. (5). Locations of five sample road networks within the research area. (**a**) Road networks of 50 km (N-S) x 50 km (E-W) in extent. (**b**) Road networks of 160 km (N-S) x 240 km (E-W) in extent.

where,

T_c = time to transport woody biomass from a particular forest cell, c (source node, c = 1, 2, 3, …, 100,061) to power plant (sink node) in hours.

Similarly, the transportation cost of woody biomass ($\$\cdot gt^{-1}$) from a forest cell (source node) to a power plant (sink node) can be determined by Equation (8).

$$TC_c = \frac{T_c \times P}{L \times f} + FC \quad (8)$$

where,

TC_c = transportation cost to transport woody biomass from a particular forest cell (source node) to a power plant (sink node) in $\$\cdot gt^{-1}$.

The minimum costs for transporting woody biomass from productive and depleted forests of an entire region (not necessarily just the cells needed for wood biomass) to four power plants (ABTB, ABFF, AGS and DDPP) were compared.

RESULTS AND DISCUSSION

Transportation Distance, Time and Cost Through Road Network

The results of the cost and time (or shortest distance) for transporting woody biomass obtained from the road network optimization model are presented in Table **1**. Table **1** shows the summary of optimized trip distance, time and transport cost from road cells to a power plant using the entire research area. The minimum time (or distance) for transporting woody biomass to each of the four power plants is zero, whereas the minimum cost is 4.85 $\$\cdot gt^{-1}$. This is because the model starts from the sink node (power plant) and the minimum value of time (or distance) in that case is taken as zero. However, some minimum fixed cost is being incurred even if we start from the sink node.

In comparison with other power plants, the maximum, median and average trip distances of transporting woody biomass feedstock to ABFF are the highest, because the power plant is located near the southwest corner in the research area and the road cells in the northeast part are far from it (Fig. **1**). On the other hand, in comparison with other power plants the maximum, median and average trip distances of transporting woody biomass feedstock to AGS are the lowest, because this power plant is located near the middle of the research area and the road cells are evenly distributed around it. The average trip time for DDPP is the lowest in comparison with other power plants, as DDPP is located near the middle of the research area and has comparatively straighter and higher class routes of transportation (Fig. **1**).

Minimum Raster Resolution

The results of analysis of variance for trip time and transportation cost for 50 km x 50 km are shown in Table **2**. The results show that both location ($p < 0.001$) and grid size ($p = 0.003$) have significant effects on trip time of woody biomass for supplying woody biomass for energy production. However, there is no interaction effect of location and grid size ($p = 0.993$) on trip time. Similarly, the results for trip distance for 50 km x 50 km raster show that location ($p = 0.015$) has a significant effect on trip distance, whereas grid size ($p = 0.228$) and the interaction of location and grid size ($p = 0.303$) does not have a significant effect on trip distance.

The results show that there is a significant difference between 100 m x 100 m grid size and 1 km x 1 km grid size for trip time and cost, but there is no significant difference for distance in a 50 km x 50 km raster. The density of roads is a key factor, which plays a vital role on the woody biomass transportation time, cost and distance. The locations having higher road density and more higher class roads, generally have lower costs of transportation (Fig. **5a**, **b**). The lengths and classes, as well as density of roads are different in different locations. So the effects of locations are significant on time, cost and distance of woody biomass transportation for energy production. The grid size (100 m x 100 m, 1 km x 1 km and 2 km x 2 km) effect is significant on woody biomass transportation time and cost, but is not significant on the distance of woody biomass transportation. A number of roads which fall within a 2 km extent of a raster road network had to be removed while using a grid size of 2 km x 2 km, because only one road could be kept in the cell. However, more roads could be retained while using both 1 km x 1 km and 100 m x 100 m grid sizes. In the road selection process, higher-class roads are given preference over lower-class roads. For example, location RN3 has a dense road network as compared to other locations, because it falls in a city area (Fig. **5a**). Therefore, many lower-class roads are removed from this location using a higher grid size. Since higher-class roads have higher driving speeds, the

Table 1. Summary of Optimized Trip Distance, Time and Transport Cost from Road Cells (Source Nodes) to a Power Plant of Wood Biomass Feedstock Using Road Network Model

Power Plant	Trip Distance (km)			Trip Time (hr)			Transport Cost ($\$\cdot gt^{-1}$)		
	Mean	Median	Max	Mean	Median	Max	Mean	Median	Max
ABTB	273.54	267.38	605.17	7.14	6.96	17.49	18.71	18.35	38.79
ABFF	280.31	288.27	606.76	7.75	7.82	19.46	19.89	20.04	42.61
AGS	217.31	214.47	453.92	6.47	6.17	16.56	17.41	16.83	37.00
DDPP	228.12	220.35	540.10	6.38	6.21	18.07	17.23	16.90	39.92

The results are based on 1 km x 1 km grid.

Table 2. Average Trip Distance, Time and Transport Cost (Standard Deviations in Parentheses) of Woody Biomass for Two Raster Networks and Various Grid Resolutions

Raster Network and Grid Size	Trip Distance (km)	Trip Time (h)	Transport Cost ($\$\cdot gt^{-1}$)
50 km x 50 km Network			
100 m x 100 m grid	32.35^{a} (2.19)	1.27^{c} (0.16)	7.31^{g} (0.31)
1 km x 1km grid	29.97^{a} (1.95)	1.12^{d} (0.13)	7.02^{h} (0.26)
2 km x 2 km grid	30.20^{a} (4.56)	1.05^{d} (0.16)	6.90^{h} (0.31)
160 km x 240 km Network			
1 km x 1 km grid	149.08^{b} (51.13)	5.09^{e} (2.16)	14.73^{i} (4.20)
2 km x 2 km grid	151.92^{b} (48.94)	5.37^{e} (2.07)	15.28^{i} (4.02)
4 km x 4 km grid	144.82^{b} (48.19)	4.35^{f} (1.82)	13.29^{j} (3.54)

Values with same letters are not significantly different at $\alpha = 0.05$. All the values of trip distance, trip time and transport cost are the average values after optimization.

biomass transportation time is lower in this location. As the biomass transportation time is less in location RN3, the cost of biomass transportation is also less in this location.

The results of analysis of variance for trip time and transportation cost for the 160 km x 240 km raster are shown in Table **2**. The results of analysis of variance for trip time

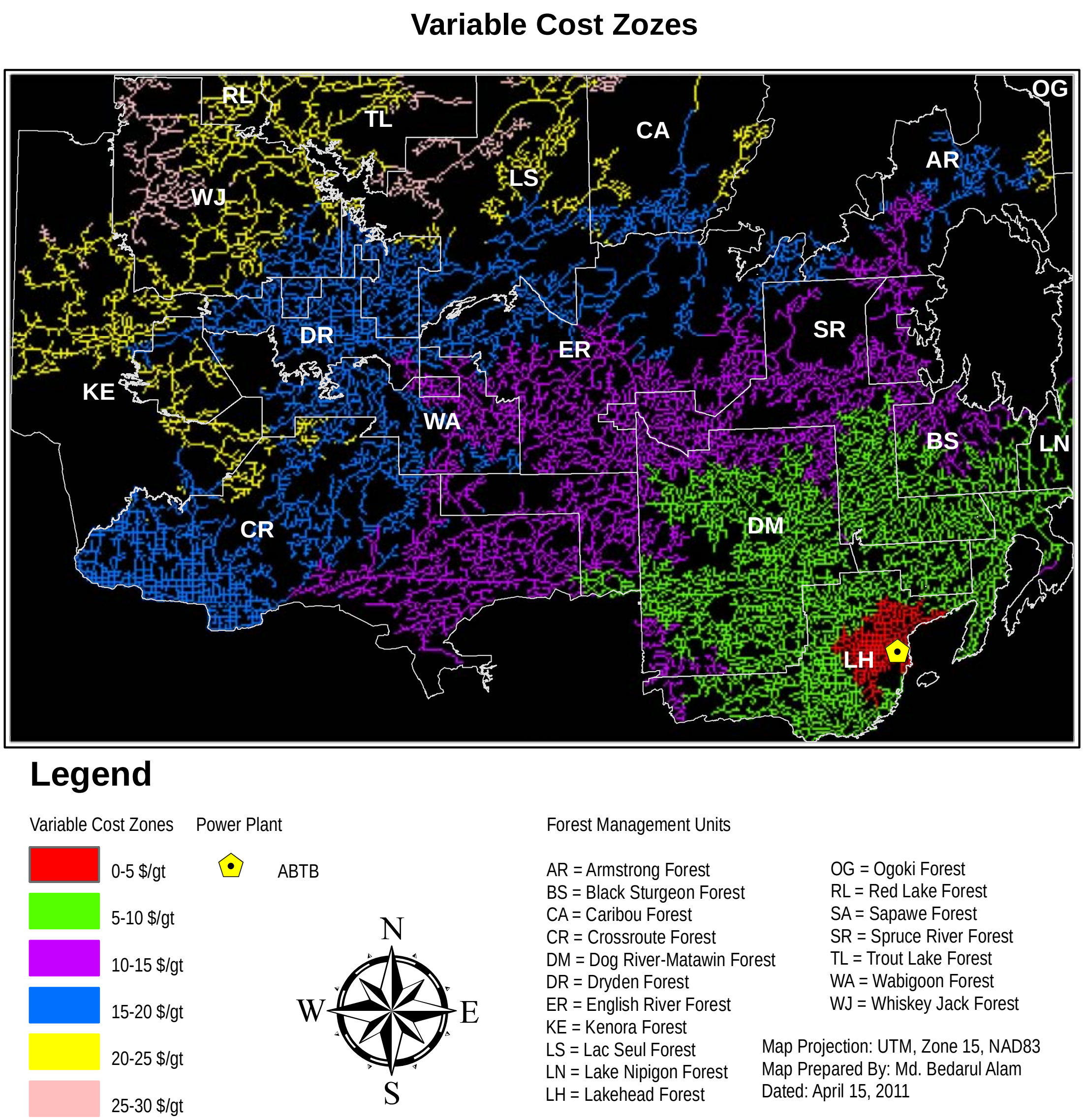


Fig. (6). Variable cost zones for the ABTB in different forest management units (FMUs).

and transportation cost for the 160 km x 240 km raster are similar to the 50 km x 50 km raster (Table **2**). These results show that both location ($p < 0.001$) and grid size ($p = 0.002$) have significant effects on trip time. But there is no interaction effect of location and grid size ($p = 0.922$) on the trip time. The results for trip distance for the same raster (160 km x 240 km) show that location ($p < 0.001$) has a significant effect on trip distance of woody biomass. However, grid size ($p = 0.761$) does not have a significant effect on the trip distance. Similarly, the interaction of location and grid size ($p = 1.00$) does not have a significant effect on trip distance. The results show that there is no significant difference between 1 km x 1 km grid size, 2 km x 2 km grid size and 4 km x 4 km grid size for trip distance in 160 km x 160 km raster. The results for both raster networks (small and larger areas) show that the 1 km x 1 km grid sized raster gives consistent results and we do not lose many roads in the analysis. The running of the network optimization model was also still efficient at a 1 km x 1 km raster; for optimization of all 26,405 road nodes it takes 75 seconds with an i7 processor. Going to a 100 m x 100 m grid and assuming linearity (linearity refers to the linear nature of the optimization model) in processing time it would take 7,500 seconds or 2.1 hours which limits the model's usefulness and user friendliness when running multiple sinks. Therefore, we adopted a grid size of 1 km^2 for all our analyses.

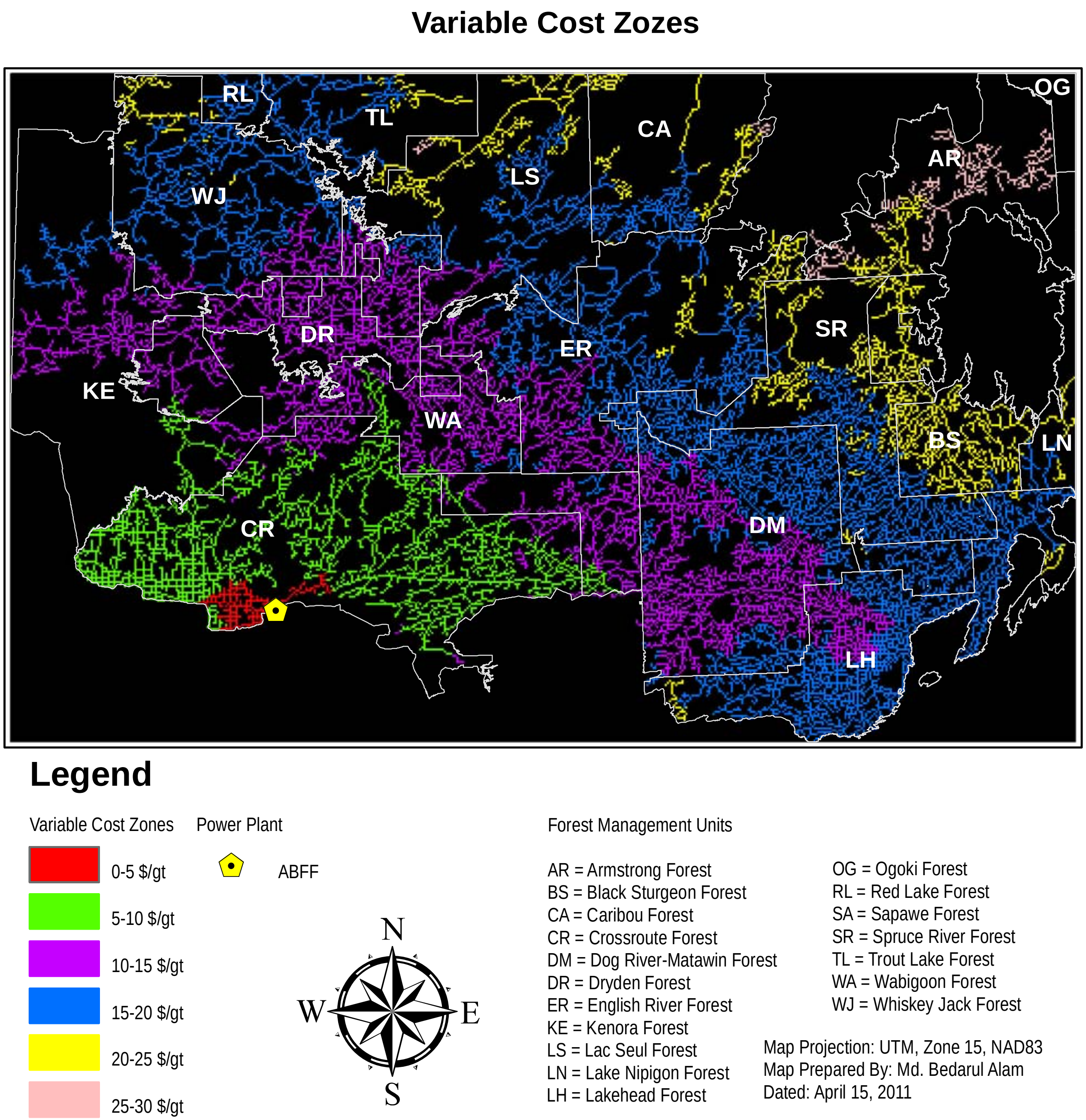


Fig. (7). Variable cost zones for the ABFF in different FMUs.

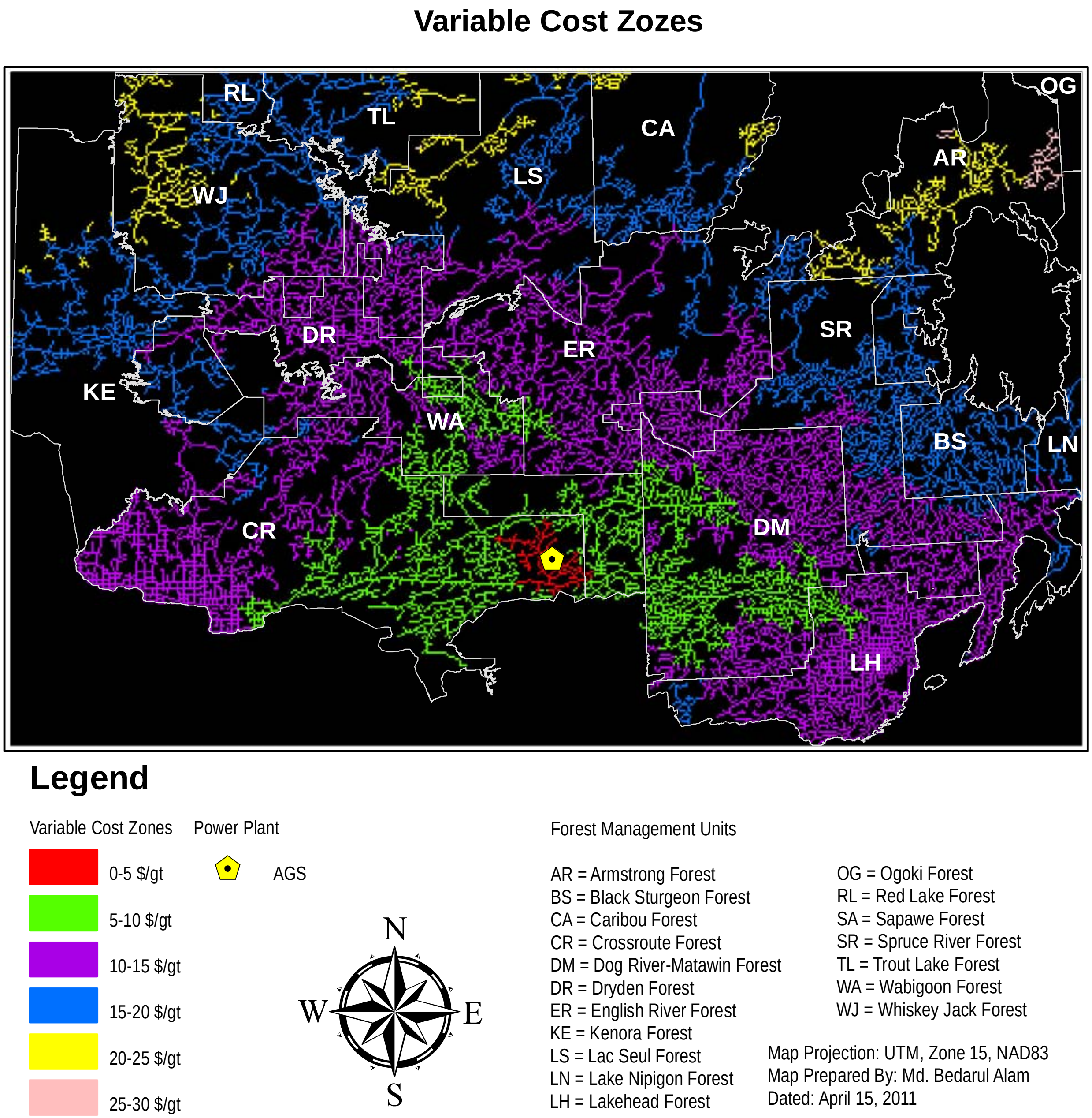


Fig. (8). Variable cost zones for the AGS in different FMUs.

Variable Cost Zones

The results of variable cost zone analysis for the research area of 324 km x 516 km are shown in Figs. (**6-9**) for ABTB, ABFF, AGS and DDPP power plants, respectively.

The variable cost zones are different for supplying woody biomass feedstock to different power plants from different locations. The traveling time through the road network from any particular geographic location to different power plants is different. The variable cost zones are related to the road network and the relative location of a power plant. These variable cost zones provide information to be used in a decision support system (DSS) for generating bioenergy in NWO. The main advantage from variable cost zone analysis is that we do not have to depend on concentric circles of varying linear distances drawn around power plants used by previous studies [36]. In this analysis, the optimization is done according to road network and not according to straight line radial distances from the power plant.

Application of Road Network Model to Transport Woody Biomass

Table **3** shows the summary of unit transportation costs ($\$\cdot gt^{-1}$) of woody biomass feedstock from productive and depleted forest cells to four power plants in NWO. The unit costs ($\$\cdot gt^{-1}$) of woody biomass transportation from productive and depleted forest cells to ABFF are in general

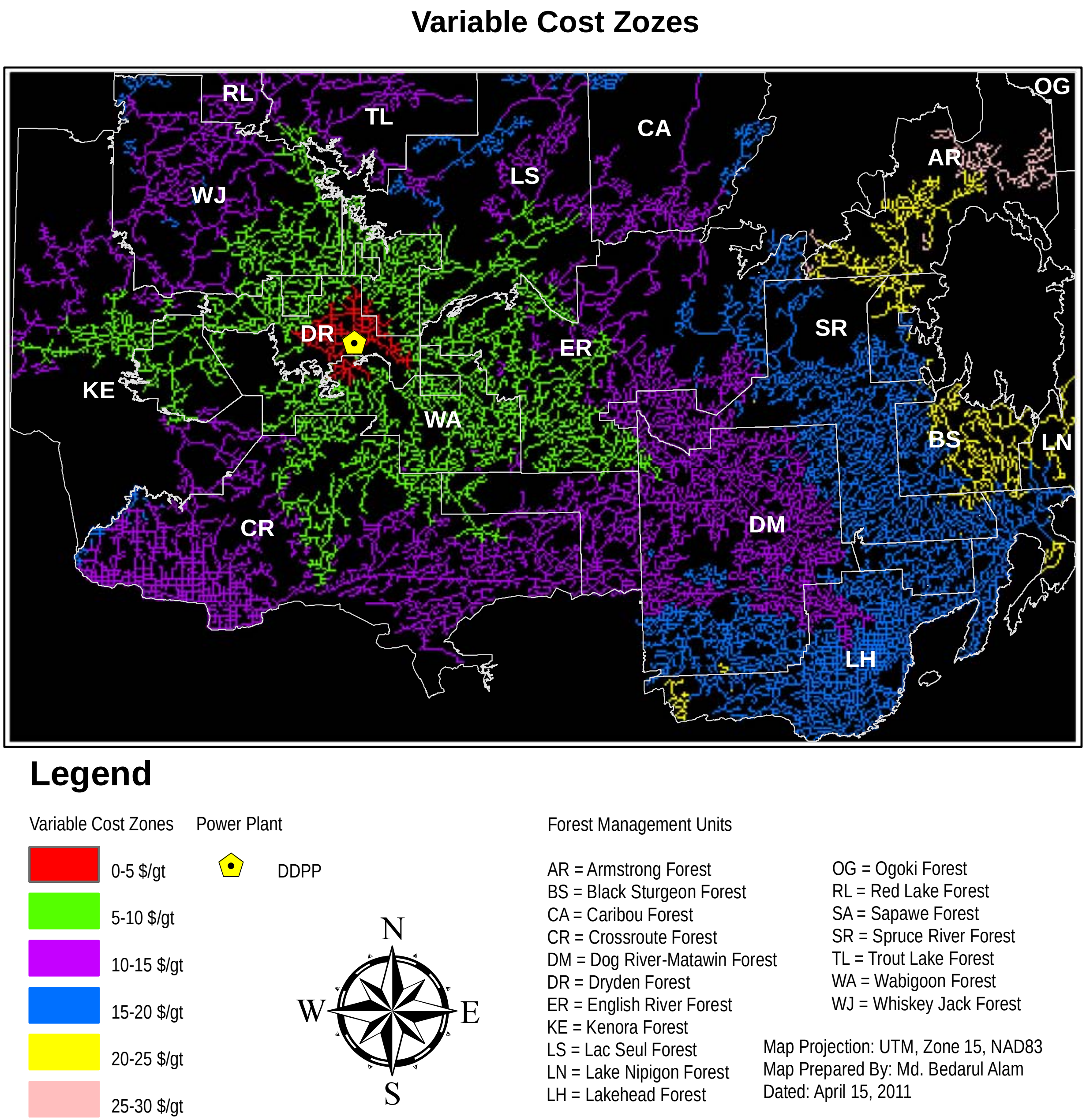


Fig. (9). Variable cost zones for the DDPP in different FMUs.

higher in comparison with the other three power plants. ABFF is located near the southwest corner of the research site, and there are not many forest cells closer to this power plant. So the unit cost ($\$\cdot gt^{-1}$) of woody biomass transportation from the forests to this plant is higher as compared to other power plants. The mean unit costs ($\$\cdot gt^{-1}$) and the median unit costs ($\$\cdot gt^{-1}$) of woody biomass transportation from productive and depleted forest cells to DDPP are lower in comparison with the other three power plants. DDPP is located near the middle of the research area, and there are many forest cells closer to this power plant along with a denser network of higher class and straighter roads.

CONCLUSIONS

This study is an application of the road network minimization algorithm for road network optimization in NWO, Canada. The minimum time and cost (or shortest distance) road network model provides efficient and effective information to be incorporated into a DSS to supply woody biomass feedstock for energy production. Careful planning of woody biomass supply logistics plays a key role in the success of a woody biomass-based industry. However, location specific data are essential for developing such road network optimization models across Canada, which can help supply woody biomass feedstock to power generating

Table 3. Summary of Transport Cost ($\$\cdot gt^{-1}$) of Woody Biomass Feedstock from Productive and Depleted Forest Cells

Power Plant	Transport Cost of Wood Biomass from Productive Forest ($\$\cdot gt^{-1}$)			Transport Cost of Wood Biomass from Depleted Forest ($\$\cdot gt^{-1}$)		
	Mean	Median	Maximum	Mean	Median	Maximum
ABTB	21.90	22.03	49.09	20.20	19.64	39.76
ABFF	22.31	22.16	53.67	20.58	20.32	53.19
AGS	20.18	19.69	48.05	18.11	17.41	47.56
DDPP	18.82	17.76	50.98	17.39	16.44	50.49

stations in a profitable and sustainable way. The variable cost zones surrounding a bioenergy power plant developed in this model can provide valuable information to be used in DSS tools. One major benefit from variable cost zone analysis is that we do not have to depend on concentric circles of varying linear distances drawn around power plants by previous studies. The optimization is done according to the road network and not according to straight line radial distances from the power plant. A grid size of 1 km^2, for road network rasters for areas ranging from 50 km x 50 km to over 300 km x 500 km in size, provides consistent and accurate results for minimum time and cost (or shortest distance) without excessive computer processing time. This road network optimization model is not only applicable for woody biomass feedstock supply but can also be used for optimizing transport of any other product through the road network. One of the limitations of this model is that it does not take into account the available supply at source nodes and demand of biomass at sink nodes. Future research in this area will incorporate these variables in the model.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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