Development of A Forest Road Erosion Calculation GIS Tool for Forest Road Planning and Design

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EXTENDED ABSTRACT

Forestry plays an important role in New Zealand's economy. The industry is almost entirely based on planted forests covering 1.8 million hectares of New Zealand. Forestry operations, however, need a dense forest road network. On hilly forested terrain, these roads are often the main source of sediment which can cause degradation of streams and waterways. Appropriate road placement and design may help reduce soil erosion and subsequent environmental impacts.

To facilitate forest road planning and reduce potential soil erosion, a Forest Road Erosion Calculation Tool (FORECALT) was developed for ArcGIS 9.1 using the Water Erosion Prediction Project (WEPP) model. The FORECALT tool uses a DEM, a GIS vector based road network map, and a series of road definition selection tools to parameterize and run the WEPP model for the combined set of all individual segments of a road network. The model is able to simulate erosion from cut slopes, road surfaces, and road drainage ditches. The model simulates both insloped and outsloped forest roads. Results of erosion and runoff per segment of forest road are displayed via the GIS interface. Outsloped forest road erosion can be displayed graphically as a map layer and total insloped forest road erosion is calculated for selected outlet points.

The FORECALT model was applied to a forest road network in the Whangapoua forest in the Coromandel Peninsula of New Zealand. Erosion and runoff predictions were made for a variety of soil and road type configurations. This application illustrates the versatility of the tool and its ability to aid in reducing environmental impacts by improving the design and planning of road networks. Sensitivity analyses of the model showed that the model is sensitive to the definition of the road segment lengths as well as DEM resolution. Segments of up to 80 meters represent the original DEM profile with reasonable accuracy; however, even small variations in calculated slope profiles may impact WEPP model erosion predictions. Runoff predictions are not affected by DEM resolution or segment length selection. Although further research is needed to understand the complex relationship between input DEM resolution and segment length selection, modelling results suggest that the model would be a valuable asset for forest managers.

1. INTRODUCTION

Forestry plays an important role in New Zealand's economy. The industry is almost entirely based on planted forests covering 1.8 million hectares of New Zealand's land area. According to the Ministry of Agriculture and Forestry, approximately 90% of this forested area is planted with fast-growing radiata pine. The yearly harvesting production in New Zealand is 21.6 million m^3 of logs. The Gross Domestic Product (GDP) from timber production accounts for approximately 3.1% of the national GDP employing over 25,000 people. Forest plantations for commercial purposes have become more important in the last 20 years. On one hand, planted forests have had a positive impact on the environment by reducing the degradation of land and sequestering carbon dioxide and therefore combating climate change. On the other,, harvesting may have a negative impact on the environment.with increased erosion leading to soil loss and degradation of the aquatic system.

Major soil loss can occur by landsliding and from road surfaces during the harvest and post-harvest periods of plantations. It is estimated that 50-90% of sediment in planted forests comes from roads (e.g Fransen et al. 2001). Sediments from roads can have a bigger environmental impact than landslide sediments because of the higher concentrations of fine sediments (Elliot et al., 1993). Sediment may affect water habitats by shortening the lives of natural reservoirs and perturbing geomorphic channel processes by excessive sedimentation.

Minimizing the impact of forest road erosion is therefore a key goal for forest planners. This can either be done by implementing potentially expensive erosion control measures after the road network has been established or by designing the forest road network in a way to minimize erosion. Both of these approaches require planners to quantify erosion produced from forest roads. Apart from setting up actual field based experiments, the prediction of erosion from forest roads is best done through modelling. Although there are a large number of tested and validated erosion models, only a few of these have been successfully used to predict forest road erosion. The most prominent model used for forest road prediction is the Water Erosion Prediciton Project (WEPP) model (Flanagan and Nearing, 1995).

The WEPP model is a physically based model that was developed for erosion prediction of cropland, rangeland, and forests. It consists of a hillslope version that predicts erosion along a hillslope profile and a watershed version that simulates erosion from the combination of hillslopes and channels in a watershed.

Elliot et al. (1993) extended the use of the model for the prediction of forest road erosion by developing specific input parameters for forest road conditions. Different road conditions, such as insloped and outsloped roads, wheel tracks, off-road deposition and roads crossing streams, were simulated using the WEPP model. The WEPP watershed model was used for insloped roads, were water flows over the road and into a ditch leading to a waterbar across the road or through a culvert. The Hillslope model was used for outsloped roads (Tysdal et al., 1997).

A variety of applications for road erosion calculations using WEPP have been developed. A web-based user interface, developed by the U.S. Department of Agriculture Forest Service, allows the user to simulate forest road erosion based on climate, soil texture and road design (Elliot, 2004). The user can use a given climate station in the US or modify the climate input. Four different soil types (clay loam, silt loam, sandy loam and loam) can be chosen for the soil input. The road design is specified by defining whether the road is insloped or outsloped. Road length and gradient, fill length and gradient, buffer length and gradient, road surface (native, gravelled, paved) and traffic level (high, low, none) also need to be defined. The outputs of the simulations are mean annual runoff, mean annual road erosion and mean annual sediment yield. Another web-based application is the X-drain model (Elliot et al., 1998). This model is used to determine optimum cross drain spacing for existing or planned roads, and for developing and supporting recommendations concerning road construction.

The WEPP Forest Road Erosion Predictor and the X-drain model are one-dimensional applications only considering one road segment with uniform conditions at a time. Best locations and optimal spacing of a road drainage system requires multiple simulations within a spatial network of roads. To address the problem of cross drain culvert spacing for larger forest road networks, Damien (2001) developed the CULvert Locator for SEDiment reduction (CULSED). This program is an interactive design tool, implemented as an ArcGIS extension. CULSED requires a GIS road layer, a stream layer, a layer with culvert locations and a DEM. It calculates the sediment delivery at each culvert location and displays the result on the computer screen. The user can add and modify cross-drain culverts and dynamically evaluate the total sediment impact to the stream network from the road system (Schiess et al., 2004). CULSED models road erosion from a georeferenced road network. However, the sediment transport and erosion calculations are a limiting factor. CULSED uses a simplified method for calculating erosion based on the Washington State Dept. of Natural Resources Manual (Damien, 2001).

The impact of forest road erosion should be analysed for a whole watershed or a complete forest road network using established erosion prediction technology. The existing WEPP applications for forest road erosion prediction consider only a single road segment. Analysing the erosion of an entire road with these tools was complicated and time consuming because segments are analysed one by one and data is entered manually. The current WEPP road erosion models have not been integrated with a GIS, and therefore spatially distributed erosion simulations of road networks were not possible with these models. The objective of this study was therefore to develop, describe, and evaluate methods of integrating WEPP and GIS for forest road erosion modelling that would enhance the planning and designing of forest road networks.

2. METHODS

An integrated WEPP-GIS model was developed that allows the user to calculate erosion and runoff for a forest road network. This model was called the Forest Erosion Calculation Tool (FORECALT). The model can be used to optimise forest road construction by analysing different road locations, culvert configurations and road types.

There are three major surface components in a forest road that erode: the road surface, the cut surface and the fill surface. The current version of our model simulates erosion of the road and cut surface, but does not take into account erosion due to fill surfaces. The interaction between the road and cut surfaces depends on the road profile, which is general categorized into outsloped and insloped road profiles. For the outsloped case, water flows from the cut surface over the road and down the hillslope. The insloped road design concentrates water from the cut and road surface in a ditch (Tysdal et al., 1997). The water drains from the ditch to an outlet where it flows down the hill away from the road. The two different road designs require different modelling approaches.

The main required inputs for the model are a Shapefile file that contains a road network, a DEM, and a layer of streams to define potential outlet points where streams and roads cross. The input road network is divided into segments (usually 50m). For each of these segments, the model calculates erosion for the road surface, the cut surface, and the ditch (if present). The results for outsloped roads can be displayed as a thematic map of erosion for each road segment. Sediment and runoff from insloped roads drain through the ditch to an outlet point. The model creates a network with all channels draining to one outlet and calculates erosion and runoff for each outlet.

Representation of the forest road for modelling

A forest road must be modelled so that the cut and road erosion surfaces represent reality, however, for modelling purposes the layout and dimension of actual lengths need to be modified (Figure 1). For modelling, WEPP defines each hillslope as a rectangular area which contributes its flow to a channel. The hillslope can either have uniform soils and cover (one overland flow element – OFE) or combinations of different types of soils or cover (multiple OFE's).

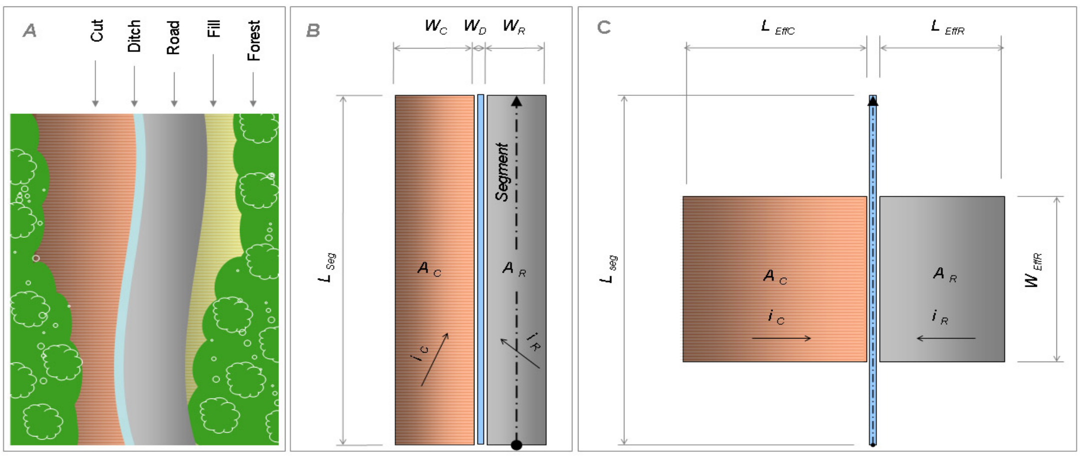

Figure 1. Schematic of an insloped forest road (A), simplified representation of the forest road (B), and representation of the forest road for modelling with WEPP (C).

For an insloped forest road, as shown in Figure 1, each cut and road segment is represented as a rectangular area draining perpendicularly into a ditch. Since the actual flows in a road may be diagonal due to the road's slope, an effective length of flow is used to define the representative rectangle for modelling with WEPP (Figure 1 C).

WEPP runs need four different input files: slope, soil, climate and management (or cover). Insloped roads need additional files that describe the structure of the watershed (interconnectivity between cut slope, road, and ditches) and the characteristics of the ditches and the culverts. A DEM and the input road shape file are required to determine the terrain slope and WEPP structure file information. FORECALT creates the necessary WEPP files and runs WEPP from a GIS modelling interface tool. The results from the WEPP calculations are imported and stored as segment attributes.

The FORECALT model has different levels of interactions between the User (Input), ArcGIS Layers, Visual Basic Programme and WEPP (Version 2004.7). The GIS programme used for the application is ESRI® ArcMap™ 9.1 including 3D Analyst and the Spatial Analyst extensions. All the applications have been programmed with Microsoft Visual Basic 6.3.

Outsloped Roads

Erosion and runoff for each segment of an outsloped road is computed with the WEPP Hillslope version. The different surfaces (cut and road) are modelled as Over Flow Elements (OFE). OFE's are hillslope segments with unique soils and management properties. WEPP calculates erosion and runoff for each segment. The results are stored as segment attributes and can be displayed as a thematic map. The total erosion of a road network is the sum of the erosion from each of the road network segments.

Outsloped roads are modelled as one surface element (Length x Width) with two OFE (Figure 2). Eqn. 1., modified from Cochrane and Flanagan (2003), can be used to determine the over flow element length.

[Eqn. 1]

$$L_{EffOFE} = \frac{(L_{EffC} \times A_c) + (L_{EffR} \times A_R)}{A_C + A_R}$$

L_{EffOFE} : Effective OFE Length

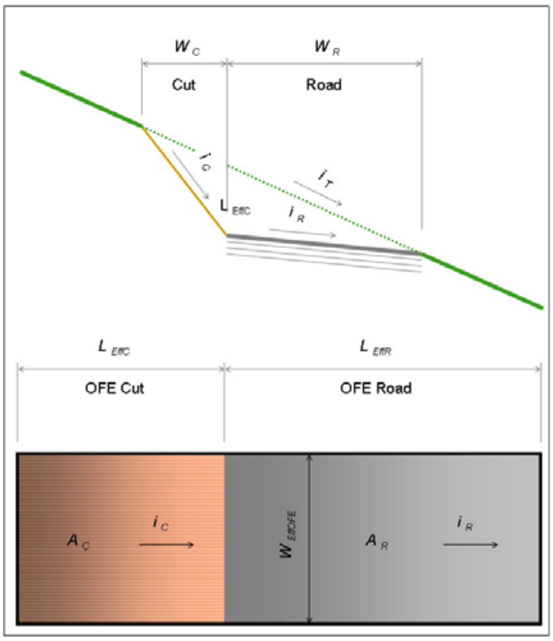

Figure 2. Cross section and surface elements with OFE cut and OFE Road for an outsloped forest road.

The FORECALT model uses Eqn 2 and 3 originally derived by Elliot et al. (1993) to describe the effective slope and length of the road

[Eqn. 2]

$$i_{EffR} = \sqrt{grad^2 + i_R^{\ 2}}$$

i_{EffR} : Effective Road slope
i_R : Road slope
grad : Segment gradient

[Eqn. 3]

$$L_{EffR} = W_R \cdot \frac{i_{EffR}}{i_R}$$

L_{EffR} : Effective Road Length
W_R : Road Width (Input value)

Cut width and OFE width for outsloped roads are set equal to the road width. These equations can also be used directly for hillslopes with one OFE, which is the case for insloped roads.

Insloped Roads

Insloped roads cannot be modelled with the WEPP Hillslope model because of erosion is contributed from a ditch that separates the road and cut slope components (Figure 3). It is therefore necessary to use the WEPP watershed model so that the interaction between different hillslopes (cut and road) and channels (ditch and outlet) can be modelled (Tysdal et al., 1997).

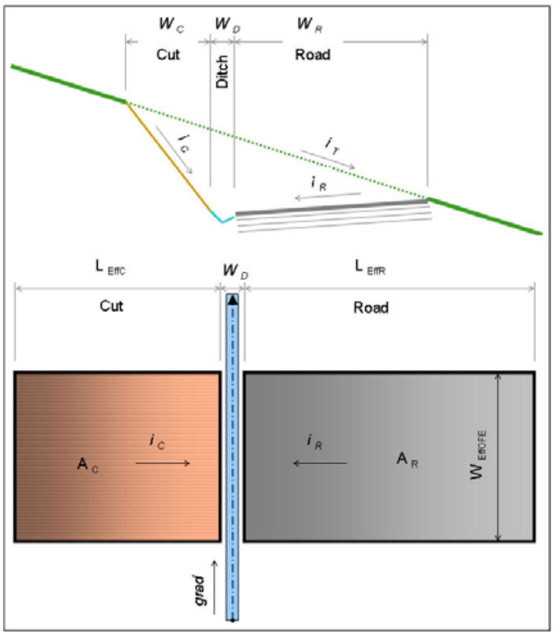

Figure 3. Cross section and surface elements (Cut and Road) of an insloped forest road.

Erosion due to insloped roads is determined in two steps. Firstly, erosion is calculated for each hillslope. Secondly, the erosion and runoff process from the hillslopes, draining through the channel to the outlet are computed with the Watershed model. The WEPP Watershed model requires additional input files describing channel and network structure characteristics. Erosion and runoff are stored as outlet attributes. The total erosion and runoff of the road network is the sum of each outlet results.

FORECALT calculates the effective OFE width and cut width using Eqns. 4 and 5.

[Eqn. 4]

$$W_{EffC} = \frac{A_c}{L_{EffR}}$$

W_{EffC} : Effective Cut Width

[Eqn. 5]

$$W_{EffOFE} = \frac{A_c + A_R}{L_{EffR}}$$

W_{EffOFE} : Effective OFE Width

FORECALT simulation

FORECALT simulates erosion and runoff from forest roads in four steps. In the first step, the input road network, DEM, and stream layers are analyzed and appropriate attributes are extracted and stored. The road segmentation process follows. During this process the road network is segmented into the user defined maximum segment length (usually set to 50m). Segments and their necessary attributes, such as road slope and cut, are calculated and stored in a newly created WEPP road GIS layer. In the third step, the user can manually add outlets and modify the calculated attributes. It is in the fourth step when actual erosion and runoff are calculated with the WEPP model. The user selects whether to run the simulation for an outsloped or inlsoped road network scenario. Results for outsloped or for insloped roads are stored as attributes in the segment or outlet layer. Segmentation and WEPP calculations can be repeated within the same project. The model output includes tabular data of erosion and runoff as well as a GIS map layer of either erosion at outlet points for an insloped road or erosion along the road for an outsloped road.

Example application of FORECALT.

An example application of FORECALT was conducted for Compartment 49 of the Whangapoua Forests in the Coromandel Peninsula of New Zealand. The catchment is 36ha in area and drains into the Waitekuri Stream, which in turn flows into Whangapoua Harbour. The soils are described as Waitekere and Rangiuru hill soils. They occur on moderately steep to steep terrain; they are similar in structure to soils on rolling hill country but are thinner due to erosion. Generally the soils consist of silt loams or brown clay with a friable, strongly develop structure, underlain by yellow-brown clay. The soils are prone to erosion, particularly during extreme rainfalls (Phillips et al., 2005).

At the time of the case study, no detailed road data was available, except a shape file with the geometry of the forest roads in the Whangapoua forest (Figure 4). The catchment was defined using the ArcGIS Watershed function based on a 10 meter DEM. All roads within the catchment were selected and used for the erosion analyses even though some are just bladed tracks constructed on ridges between two different catchments used to allow a bulldozer to be a back anchor/rope support for the cable hauler (1, 5, and 6 in Figure 5). Therefore, it is difficult to estimate whether the road surfaces contribute to total erosion in the catchment. The total length of the selected roads is 3493 meters. Input data for the model is shown in Table 1.

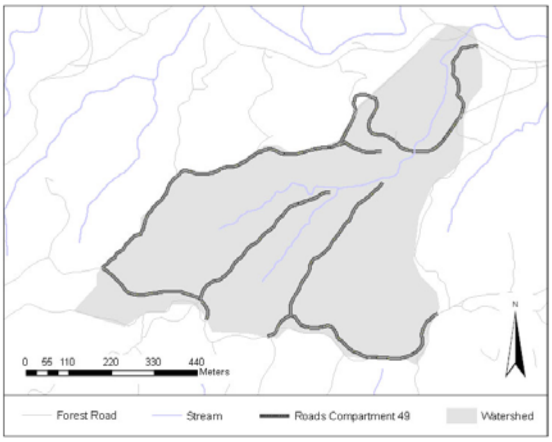

Figure 4. Road layout of example application of FORECALT in the Whangapoua forest

Table 1. Input values for example application using FORECALT

Road Geometry	Road Width Road Slope Ditch Width	5.00 m 3 % 0.30 m
Cut Geometry	Cut Gradient No Cut below ½ Cut below	60 deg 5 deg 20 deg
Design		Insloped Outsloped
Road Surface		Native Gravelled
Soil Type		Clay Loam Silt Loam Loam
Climate File	Whangapoua Forest rainfall and other Whitianga Airport data	2001-2002

The simulations were run for both insloped and outsloped road designs. The total erosion and runoff was calculated for Clay Loam, Silt Loam, and Loam type soils. Two different simulations were carried out for the years 2001 and 2002.

3. RESULTS AND DISCUSSION

The FORECALT segmentation procedure calculated the effective dimensions of the road surface and the cut surface. The road network segmentation, the road cut widths (as calculated from the DEM), and insloped road outlets are shown in Figure 5. Most of the calculated cut widths were less than 1 meter or even zero because the DEM shows that road features 1, 5 and 6 (Figure 5) follow the ridge of the catchment. Road features 3 and 4 have larger cut areas with cut width up to 5 meters. This section of the road is situated in a versant. Large cut areas appear more likely in such terrain conditions and therefore the model seems to be simulating these well. However, on steep versant, FORECALT might calculate too large cut widths, especially when the user has specified a low value for the cut slope input value. For those situations the user should verify and change cut slope values as needed.

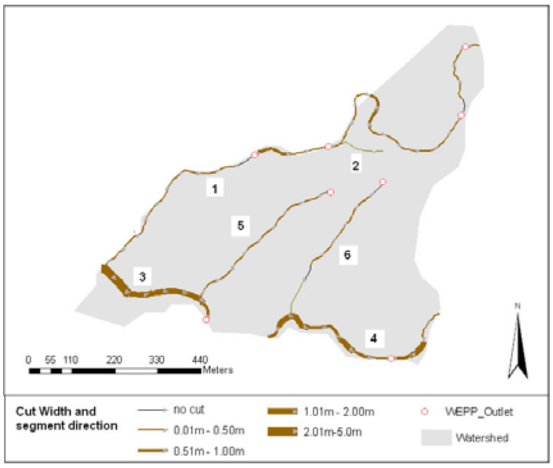

Figure 5. Segmentation and cut width calculation of road layout.

Results from the FORECALT Whangapoua catchment application are shown in Table 2 for the 2 year period. The range of results varies from 0 to 1000t for the whole catchment road network. These results were dependent on the selection of road type (insloped, outsloped) and soil type. Measured sediment yield at the outlet of the catchement for the same period was 41t (Phillips et al., 2005). This would match the situation if the roads were silt loam and gravelled and contributed all erosion directly to the outlet of the catchment. It must be emphasized, however, that erosion is calculated for the cut, road and the ditch and processes from the outlet points to the stream have not been modelled and neither have overland erosion processes. It can be assumed that a very large percentage of the FORECALT's estimated erosion for both insloped and outsloped roads never reaches a stream. The application, however, shows that erosion on a complete road network can be modelled with FORECALT and therefore it can be a useful tool for planning and management.

The example application was run using a road segmentation length of 50m. Initial sensitivity tests show that the model is sensitive to the selection of the segmentation lengths; however, the sensitivity is related to the steepness of the terrain. When working with a DEM resolution of 10m, the model seems to give consistent erosion results for segments in the range between 20 and 70 for steep slopes. The segmentation length selection is more sensitive when simulations occur in medium slopes and not very sensitive at low slopes. The model, however, seems to represent topography fairly accurately with segments up to 80m lengths. Runoff prediction is not sensitive to simulations with different segment lengths.

Table 2. Simulated erosion and runoff for insloped and outsloped road designs over a variety of road and cut soil conditions.

		Total	
Soil	**Slope**	**Erosion [kg]**	**Runoff [m^3]**
Clay Loam	Insloped	1,103,700	26,021
Natural	Outsloped	901,807	24,067
Silt Loam	Insloped	1,119,300	19,749
Natural	Outsloped	944,578	18,648
Sandy Loam	Insloped	119,600	1,946
Natural	Outsloped	110,608	1,836
Loam	Insloped	1,209,100	22,472
Natural	Outsloped	1,070,904	21,244
Clay Loam	Insloped	152,600	3,892
Gravelled	Outsloped	8,212	898
Silt Loam	Insloped	45,400	1,275
Gravelled	Outsloped	0	0
Sandy Loam	Insloped	2,700	140
Gravelled	Outsloped	0	0
Loam	Insloped	51,500	1,601
Gravelled	Outsloped	214	147

4. CONCLUSIONS AND RECOMMENDATIONS

The FORECALT model enables the estimation of erosion from complete forest road networks via a GIS – WEPP interface. The application of the tool shows its versatility in predicting erosion and runoff for a wide range of scenarios, including variations in road configurations (insloped and outsloped). Sensitivity tests, however, show that the erosion predictions are sensitive to the selection of road segment lengths, particularly in mid range slope angles. The unique interactions between DEM resolution and a selected segment length will result in the calculation of a specific slope profile for the road. Varying selected segment lengths or DEM resolution will result in variation in the calculated slope profile. WEPP is able to predict deposition as well as erosion and small variations in input slopes may trigger deposition which may impact the overall sediment yields from insloped road outlet points. Therefore a change in segment length will cause a slightly different slope profile to be calculated and therefore result in either an increase or decrease in erosion predictions. The WEPP calculation of runoff is not very sensitive to slope changes and therefore segment length selection does not affect runoff predictions. One way to overcome these modelling issues is to set hard limits on the relation between DEM resolution and segment lengths. Further research, however, is needed to understand the interactions of DEM resolution, terrain steepness, and segmentation length selection on forest road erosion prediction. Furthermore, the integration of this erosion model to a surface erosion and landslide catchment model would prove valuable to further our understanding of the integrated erosive processes that may be occurring in a forested catchment.

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