Non-linear world - a shift from linear to non-linear modelling of natural environments

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Abstract

Majority of currently applied environmental models relay on linear relations between environmental endmembers. In this research, a detailed and comprehensive comparison between linear (L) and non-linear (NL) models are presented. The L and NL models are realized in a framework of Artificial Neural Networks (ANN). The evolution process of the ANN-L and ANN-NL models is based on estimation of fractional snow cover through data-fusion between high resolution (IKONOS) and medium resolution (Landsat TM/ETM+) remotely sensed images. The statistical measure values of R2, RMSE, MAE, Accuracy, Precision, Recall, and Specificity indicate better performance of the ANN-NL model in comparison to the ANN-L in estimation of ANN Landsat-FSC. The presented results, strongly indicate that to fully capture, untangle, and characterize internal environmental relations high-sensitivity non-linear models are required. Non-linear relations are particularly visible the complex in alpine-forested environments.

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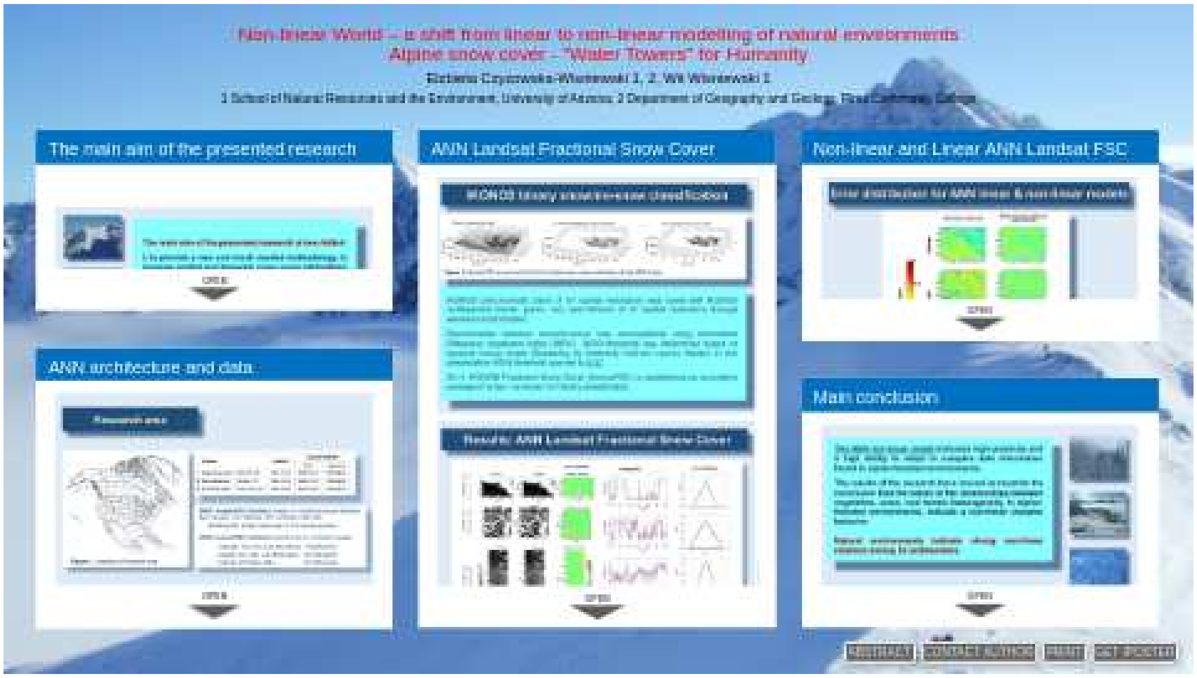
Non-linear World – a shift from linear to non-linear modelling of natural environments Alpine snow cover - "Water Towers" for Humanity



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THE MAIN AIM OF THE PRESENTED RESEARCH




The main aim of the presented research is two-fold:

I. to provide a new and much needed methodology to improve spatial and temporal snow cover estimations in the complex alpine-forested regions,

II. to provide a comprehensive comparison between linear and non-linear models set in the Artificial Neural Networks (ANNs) framework to estimate Landsat Fractional Snow Cover (Landsat-FSC) in complex alpine-forested environments.

The ANN Landsat-FSC was delivered through data fusion between IKONOS ground-based binary classification snow/non-snow (1 m spatial resolution) and Landsat multispectral images (30 m spatial resolution).

ANN ARCHITECTURE AND DATA

Research area

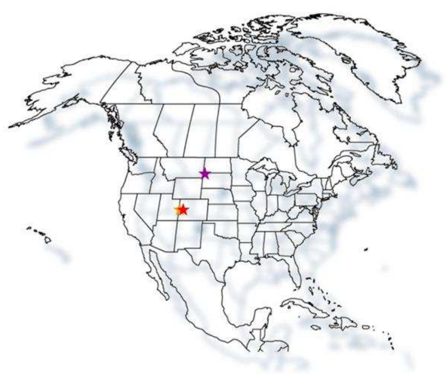


Figure 1. *Locations of research area.*

Datasets		IKONOS	Landsat TM/ETM+	
			'snow'	*'vegetation'*
★ **Fresh snow cover**	*Telluride, CO*	2008-10-12	2008-10-12	2007-09-08
★ **Full snow cover**	*Creede, CO*	2000-12-18	2000-12-18	2002-08-26
★ **'Old' snow cover**	*Black Hills, WY*	2003-02-25	2003-02-26	2002-09-03

ANN Landsat-FSC training is based on combined image datasets from Creede, CO, Telluride, CO, and Black Hills, SD

98 000 points (pixels) were used in the training process.

ANN Landsat-FSC validation is performed on individual images:

- Telluride, CO, San Juan Mountains, 79 000 points
- Creede, CO, San Juan Mountains, 159 000 points
- Dakota, WY, Black Hills, 149 000 points.

Data input and target for ANN Landsat FSC

The ANN training input data contained: 6 spectral bands from Landsat TM/ETM+ images representing snow and vegetation cover. Additionally, slope, aspect, and shadow distribution was added based on NED DEM data. In total, 15 independent inputs were inserted to the ANN during the training process – *section B of figure 2.*

Target data were represented by IKONOS-FSC – *section A of figure 2 & figure 4.*

The input and target data were rescaled to 30 m nominal resolution of Landsat TM images. The input data were rescaled to z-score to enable easier interpretation of ANN weights by making them relative to a known numerical scale.

Training input data contained 98 000 pixels, validation data set contained 297 728 pixels

Information flow for ANN Landsat FSC

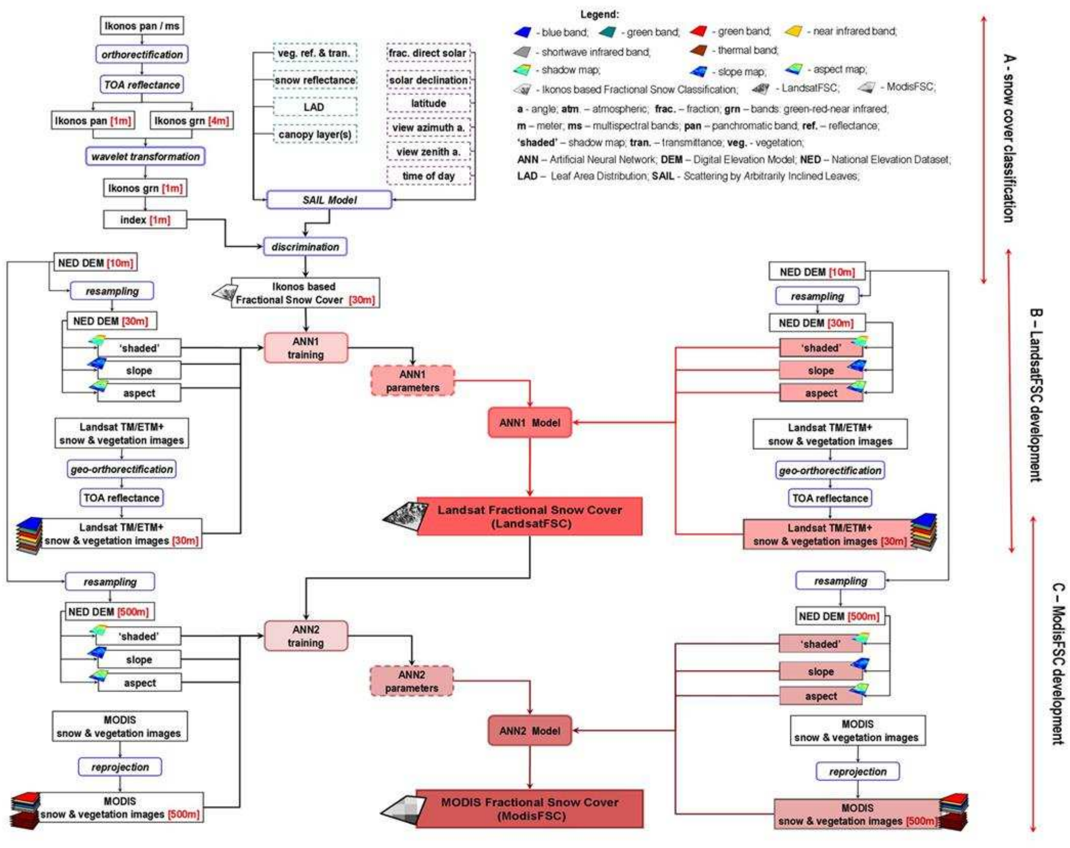


Figure 2. *Information flow for ANN Landsat-FSC and Modis-FSC development.*

ANN architecture for Landsat FSC

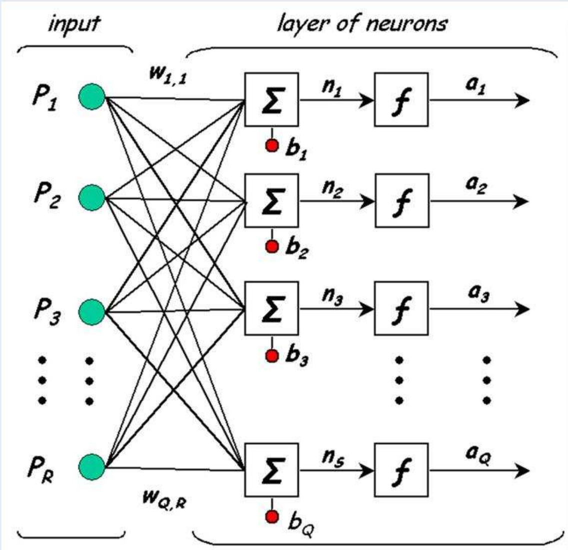


Figure 3*. The architecture of one layer in a multilayer feedforward perceptron.*

P1, P2, .., PR – input; $w_{1,1}$ .., $w_{Q,R}$ – weights; Σ- sum of the weighted inputs; b – bias; Q – number of neurons; a – network output; ƒ- activation function; R – number of elements in input vector.

In our research we applied a **fully connected feedforward perceptron with backpropagation.**

The main architecture applied was 35-11-7, it means 3 hidden layers, with 35, 11, and 7 neurons in the first, second, and third layer, respectively.

The sigmoidal activation function (Matlab function: *tansig*) was assigned to the first and second layer, and linear function (Matlab function: *purelin*) to the third layer.

The Levenberg-Marquardt back-propagation, representing a gradient-based learning algorithm, was used during the training process.

To overcame overtraining, the early stopping with cross validation method was used.

ANN LANDSAT FRACTIONAL SNOW COVER

IKONOS binary snow/no-snow classification

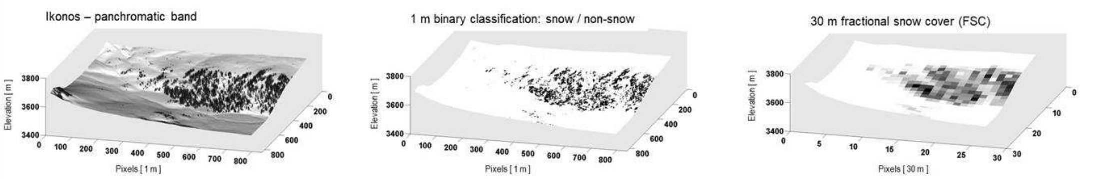


Figure 4. *IkonosFSC as a ground truth for Landsat snow cover estimation during ANN fusion.*

IKONOS panchromatic band (1 m^2 spatial resolution) was fused with IKONOS multispectral bands: green, red, near-infrared (4 m^2 spatial resolution) through *wavelet transformation*.

Discrimination between snow/no-snow was accomplished using Normalized Difference Vegetation Index (NDVI). NDVI threshold was determined based on spectral mixing model (Scattering by Arbitrarily Inclined Leaves Model). In this presentation NDVI threshold was set to 0.07.

30 m IKONOS Fractional Snow Cover (IkonosFSC) is established as cumulative average of snow / no-snow 1m^2 binary classification.

Results: ANN Landsat Fractional Snow Cover

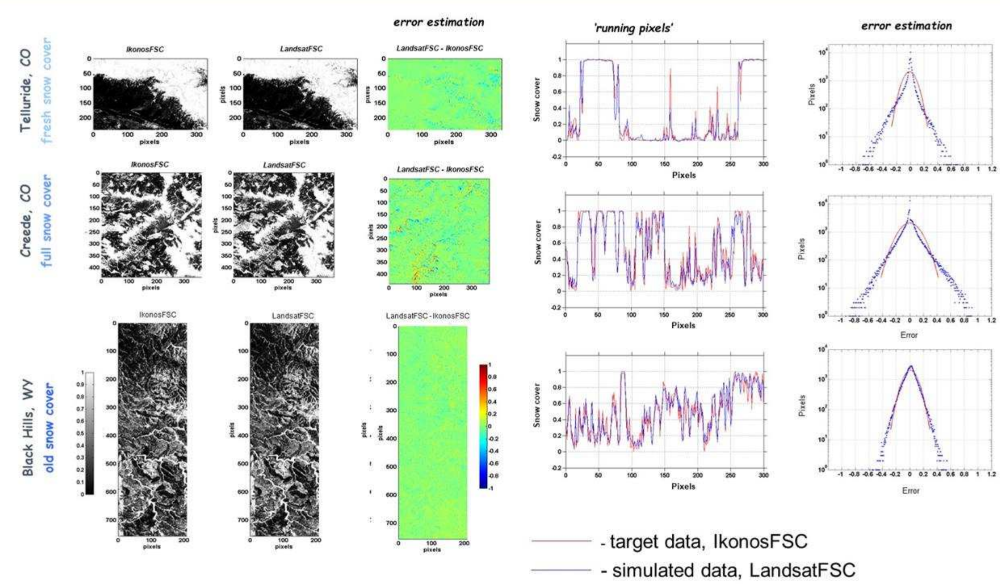


Figure 5. *ANN Landsat-FSC estimations for Telluride, Creede, CO and the Black Hills of South Dakota, WY*

The ANN Landsat-FSC model represents ***the first attempt*** to develop an estimator of fractional snow values from actual ground equivalent reference data and non-linear modeling

It is the first endeavor to estimate FSC values by combining terrain and reflectance data

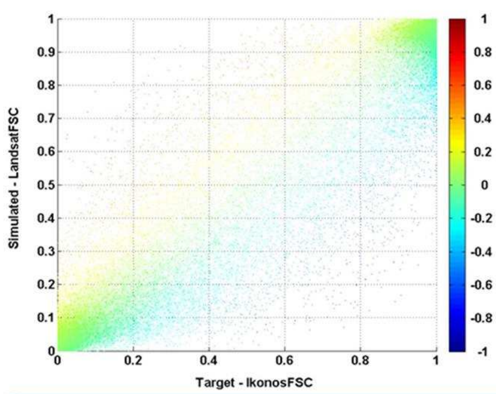
ANN Landsat-FSC exhibits:

very low error values: **mean error ~ 0.1%**

high correlation with the ground equivalent reference: **R^2 ~ 0.9**

Error distribution

Telluride, the San Juan Mountains, fresh snow cover



R^2 = 0.96

RMSE = 0.08

MAE = 0.05

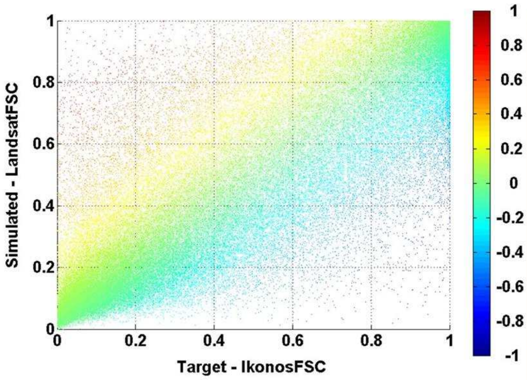
mean error = -0.014

good adjustment to complex terrain

good mapping of non-snow

Figure 6. *The scatter plot of error distribution in ANN Landsat FSC estimation for fresh snow cover conditions; Telluride, CO. For additional details please see figure 5.*

Creede, the San Juan Mountains, fully developed snow cover

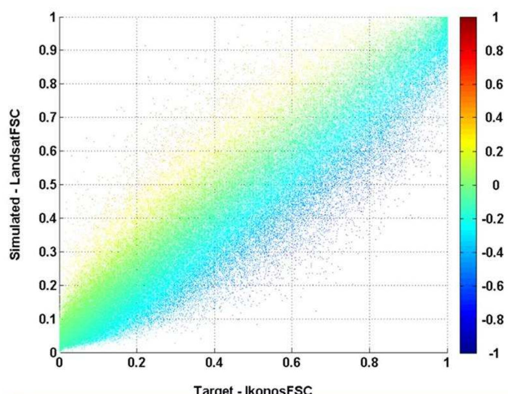


R^2 = 0.87
RMSE = 0.14
MAE = 0.09
mean error = 0.001

good adjustment to complex terrain
robust to shadow distribution

Figure 7. *The scatter plot of error distribution in ANN Landsat FSC estimation for fully developed snow cover; Creede, CO. For additional details please see figure 5.*

Dakota, Black Hills of South Dakota, old snow cover



R^2 = 0.89
RMSE = 0.09
MAE = 0.07
mean error = 0.008

good adjustment to hilly terrain
robust to mixed-forest conditions

Figure 8. *The scatter plot of error distribution in ANN Landsat FSC estimation for old snow cover conditions; Dakota, WY. For additional details please see figure 5.*

ANN Landsat FSC and terrain information

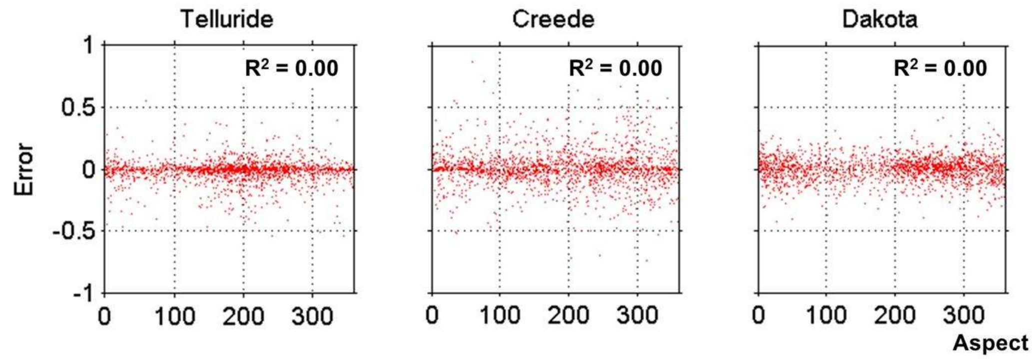


Figure 9. *The scatter plot between error in ANN Landsat FSC estimation and aspect.*

Error values of ANN Landsat FSC estimates are *independent* on aspect

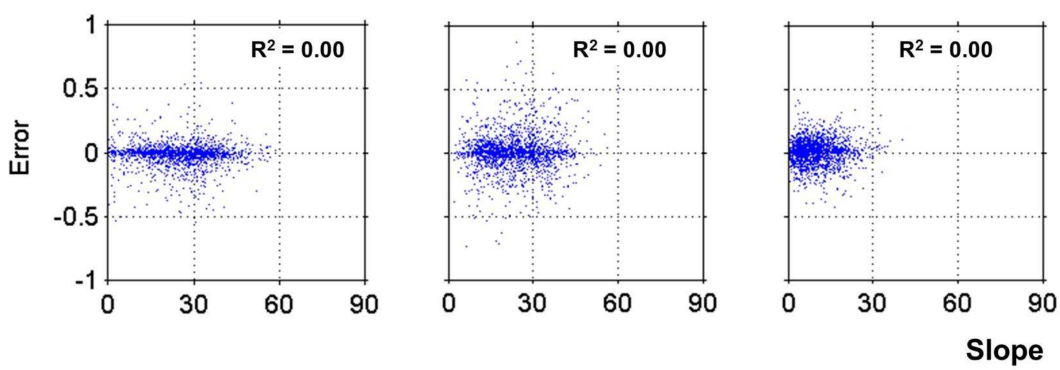


Figure 10. *The scatter plot between error in ANN Landsat FSC estimations and slope.*

Error values of ANN Landsat FSC estimates are *independent* on slope

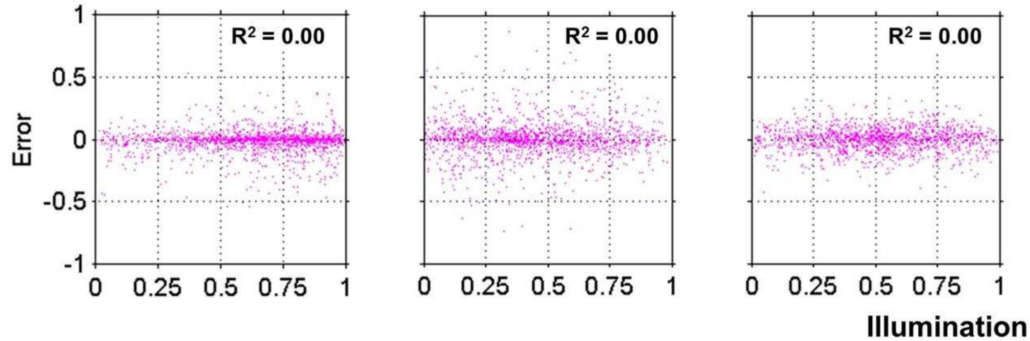


Figure 11. *The scatter plot between error in ANN Landsat FSC estimations and illumination.*

Error values of ANN Landsat FSC estimates are *independent* on illumination

ANN Landsat-FSC model delivers robust estimates of snow cover distribution which are independent on snow conditions and environmental heterogeneity

NON-LINEAR AND LINEAR ANN LANDSAT FSC

Error distribution for ANN linear & non-linear models

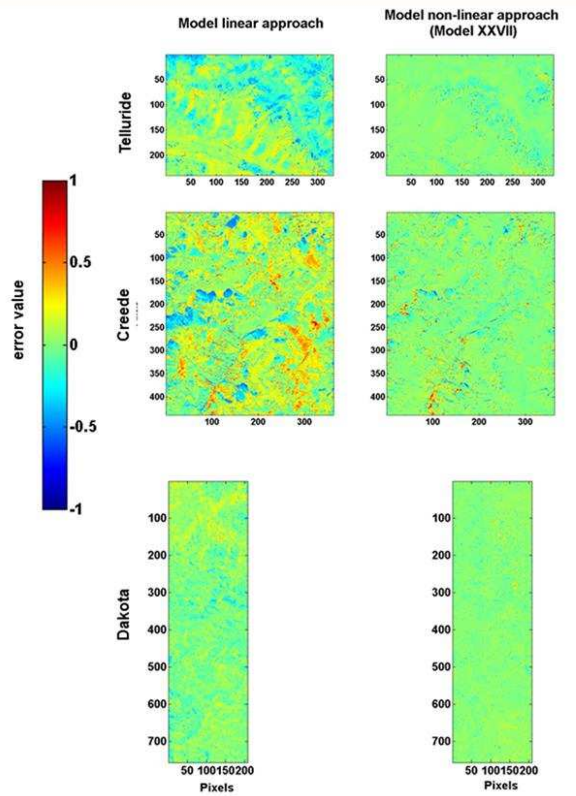


Figure 12. *Error distribution in ANN Landsat FSC estimations for linear and non-linear models for three research sites.*

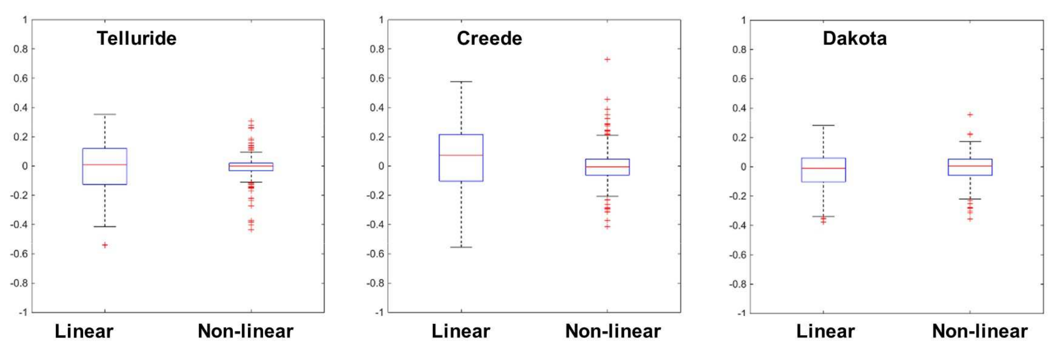


Figure 13. *Error bars for ANN Landsat FSC estimations for linear and non-linear models for three research sites.*

Both ANN Landsat-FSC models, ANN Landsat-FSC $_{non\text{-}linear}$ and ANN Landsat-FSC $_{linear}$, used the same ANN architecture and the same input data (15 data inputs) to simulate Landsat FSC. The only difference between both models are activation functions.

In ANN LandsatFSC $_{linear}$ model – a linear activation function was used during the training process.

ANN LandsatFSC $_{linear}$ model indicates significantly lower performance when compared to ANN LandsatFSC $_{non\text{-}linear}$ model.

MAIN CONCLUSION

The ANN non-linear model indicates high plasticity and a high ability to adopt to complex data information found in alpine-forested environments.

The results of the research have moved us towards the conclusion that the nature of the relationships between vegetation, snow, and terrain heterogeneity in alpine-forested environments, indicate a non-linear complex behavior.

Natural environments indicate strong non-linear relations among its endmembers.

"Mountains are environmental sky-islands, and research investigating their distinct compound complexity needs 'sky-island' specific input data and methodologies"

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ARIZONA NASA SRP Mountain Studies Institute SAN JUAN MOUNTAINS COLORADO



ABSTRACT

Majority of currently applied environmental models relay on linear relations between environmental endmembers. In this research, a detailed and comprehensive comparison between linear (L) and non-linear (NL) models are presented. The L and NL models are realized in a framework of Artificial Neural Networks (ANN). The evolution process of the ANN-L and ANN-NL models is based on the estimation of fractional snow cover through data-fusion between high resolution (IKONOS) and medium resolution (Landsat TM/ETM+) remotely sensed images. The statistical measure values of R^2, RMSE, MAE, Accuracy, Precision, Recall, and Specificity indicate better performance of the ANN-NL model in comparison to the ANN-L in the estimation of ANN Landsat-FSC. The presented results, strongly indicate that to fully capture, untangle, and characterize internal environmental relations high-sensitivity non-linear models are required. Non-linear relations are particularly visible the complex in alpine-forested environments.