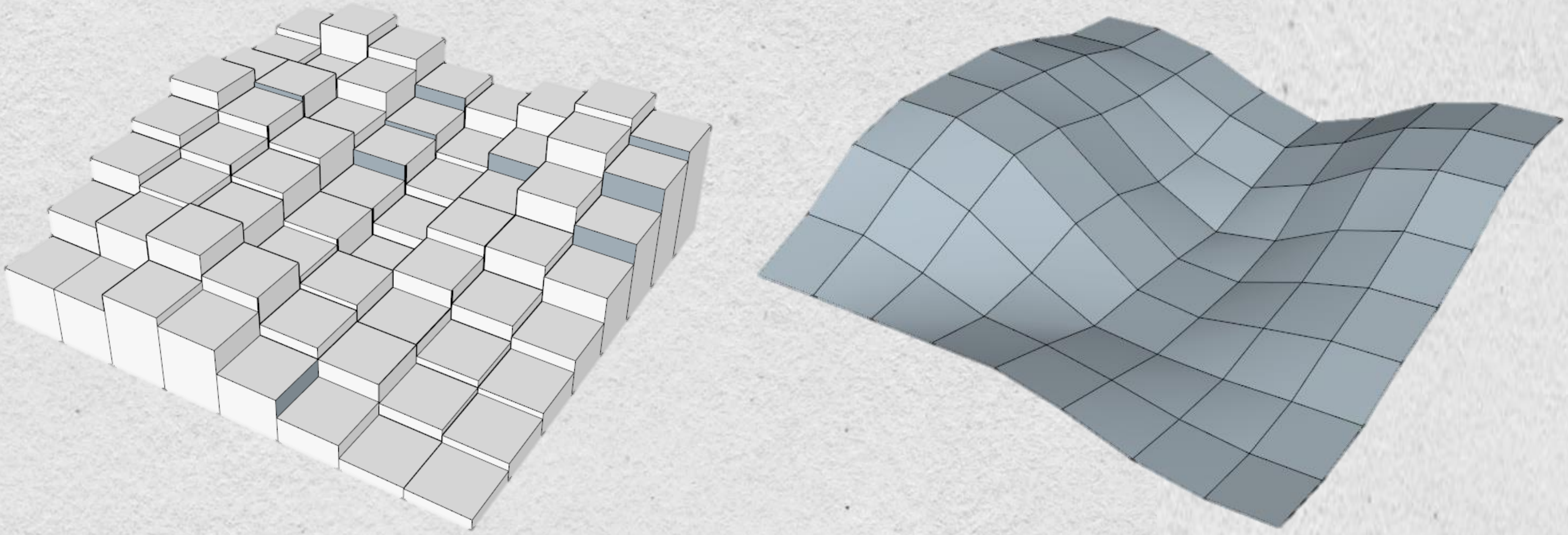
Nov 2nd, 2018
Ph.D. Defense
Boulder, Colorado

Cross-Scale Analysis of Surface-Adjusted Measurements in Digital Elevation Models



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Introduction (Research Goals)

- To advance understanding of how error is introduced in terrain-measurement when the rigid pixel paradigm is assumed to be correct.
- To compare a set of surface-adjusted measurements (elevation and surface area) that incorporate slope and curvature to minimize errors.
- To examine the sensitivity of surface adjustment to different interpolation methods, different contiguity configurations, different terrain types and a progression of spatial resolution.
- To examine the balance between the increased computations needed to measure surface-adjusted measurements against the improvements in accuracy.

Introduction (Research Questions)

- How can surface-adjusted elevation and area be most accurately estimated from a DEM? What is the best mathematical model to reconstruct the surface of a DEM cell to estimate elevation, and surface area?
- How does DEM uncertainty vary with changing spatial resolution? And does this vary with the method of surface adjustment, and/or terrain roughness?
- What computational complexity does the surface-adjusted paradigm add to computations for estimating elevation and surface area? And does the added complexity vary with resolution and geographic conditions?

Introduction (Previous Work)

- Interpolation methods can be used to relax the rigid pixel assumption and reconstruct the surface of a pixel

Li (1993) Li, Zhu, and Gold (2004)	Linear interpolators are the least misleading and most reliable methods, and high-order polynomials can lead to dramatic oscillations that do not reflect actual elevations.
Wood (1998)	Use biquadratic interpolation for calculating slope and curvature
Kidner et al.(1999) Kidner (2003) Rees (2000)	Higher order polynomials always lead to better results than linear polynomials
Shi and Tian 2006	A flat terrain can be well modeled using a lower-order polynomial, while a higher-order polynomial is more applicable to rough terrains
Liu, Hu, and Hu (2015)	Linear interpolation is the only method that preserves the inherent characteristics of terrain

Organization

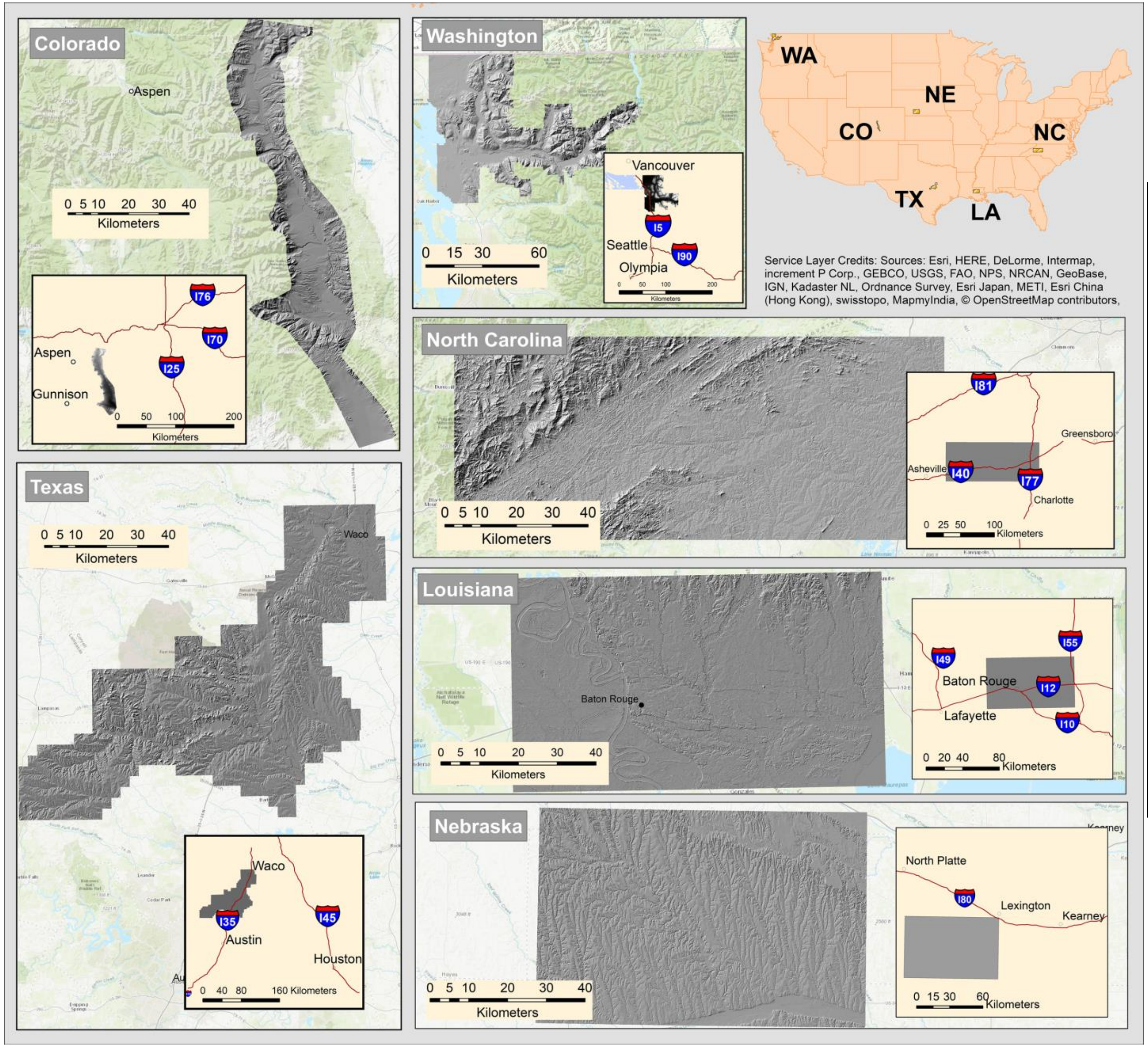
Intro
Elevation
Area
Summary

- Progression of **four** resolutions (10 m ,30 m, 100 m, 1,000 m)
- **Six** terrain samples of varying slope, elevation, roughness
- Compare **five** discrete and continuous interpolators within **five** neighborhood configurations

- Experiment 1: **Surface-Adjusted elevation**
- Experiment 2: **Surface-Adjusted area**

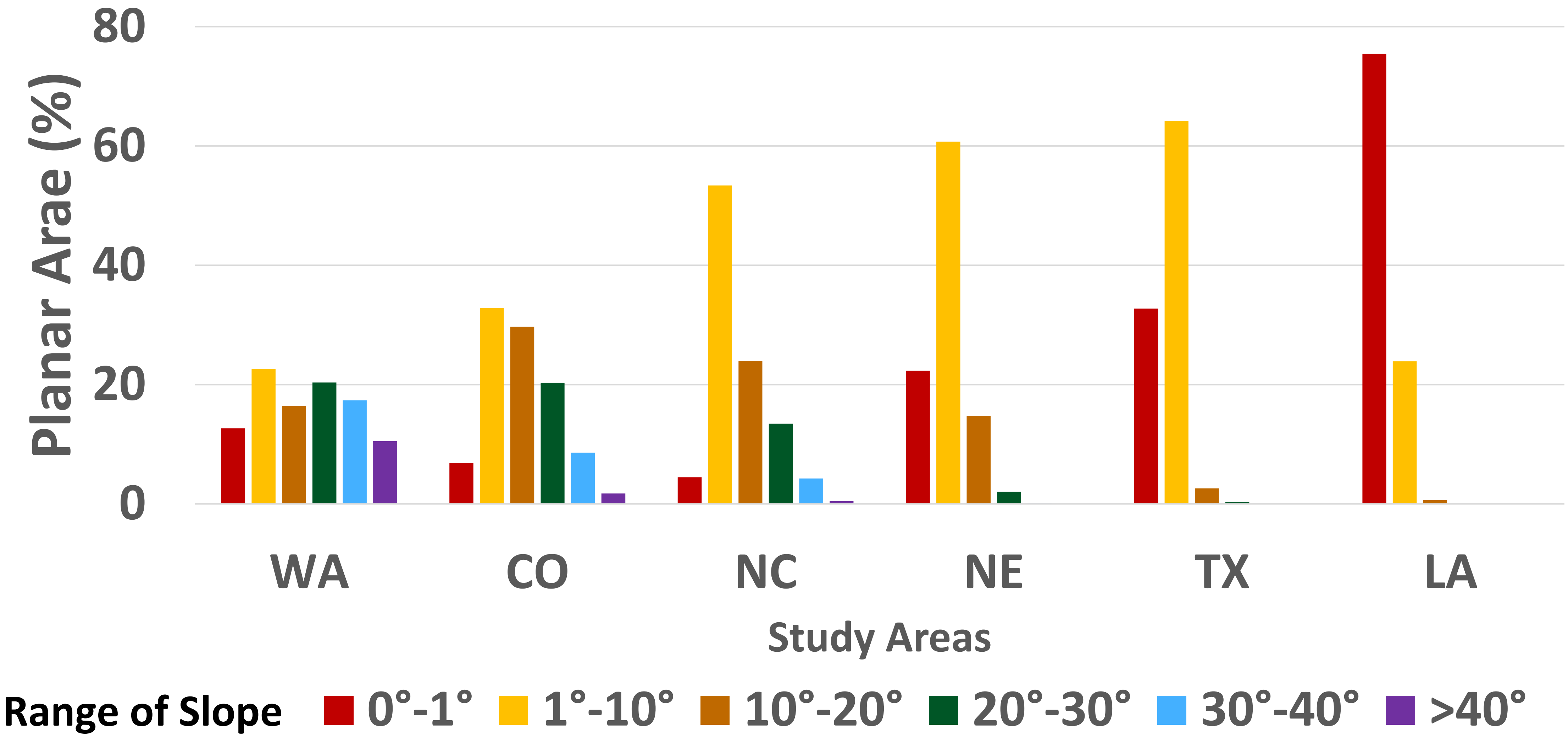
- Sequential processing for elevation, parallel for surface area

Data Sets and Study Areas

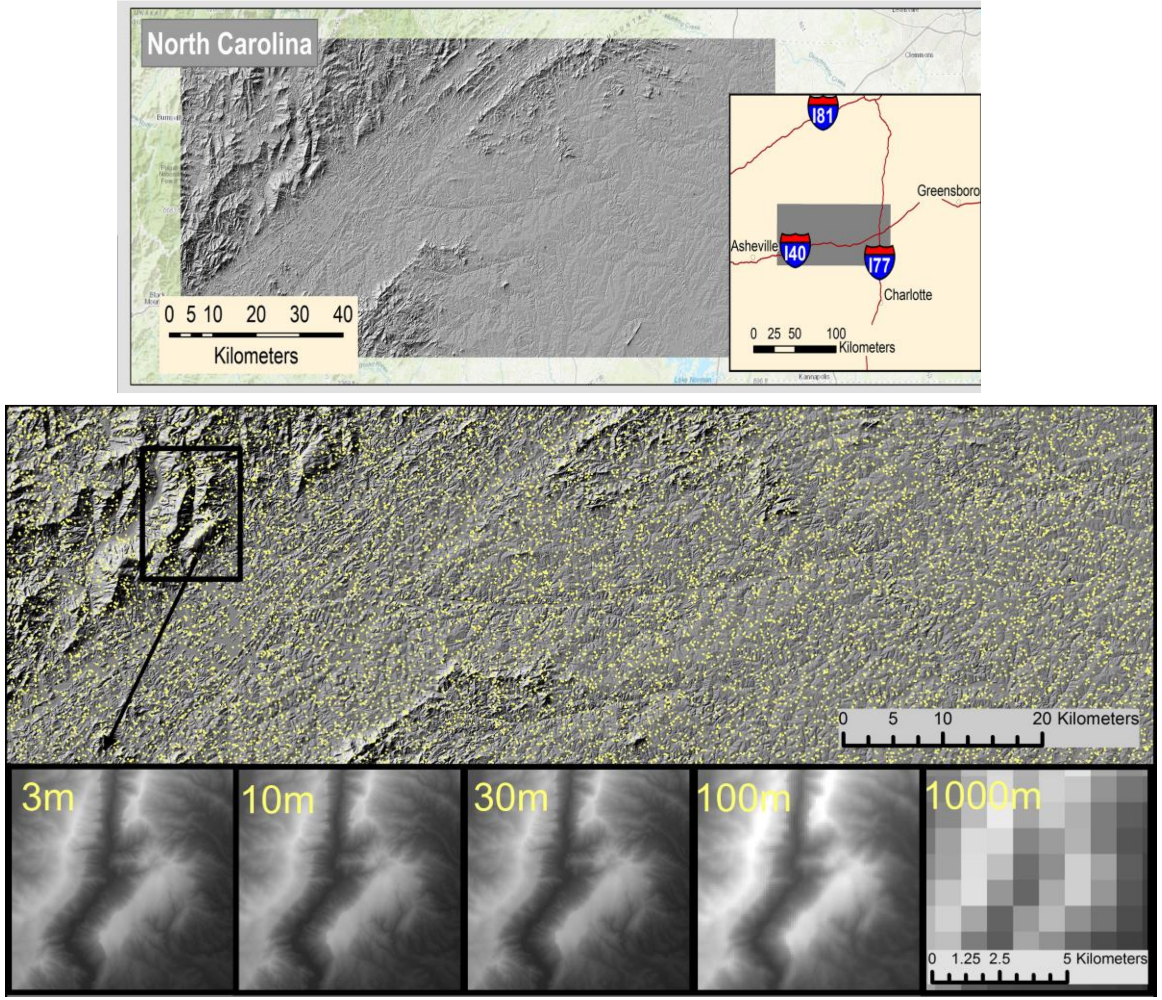


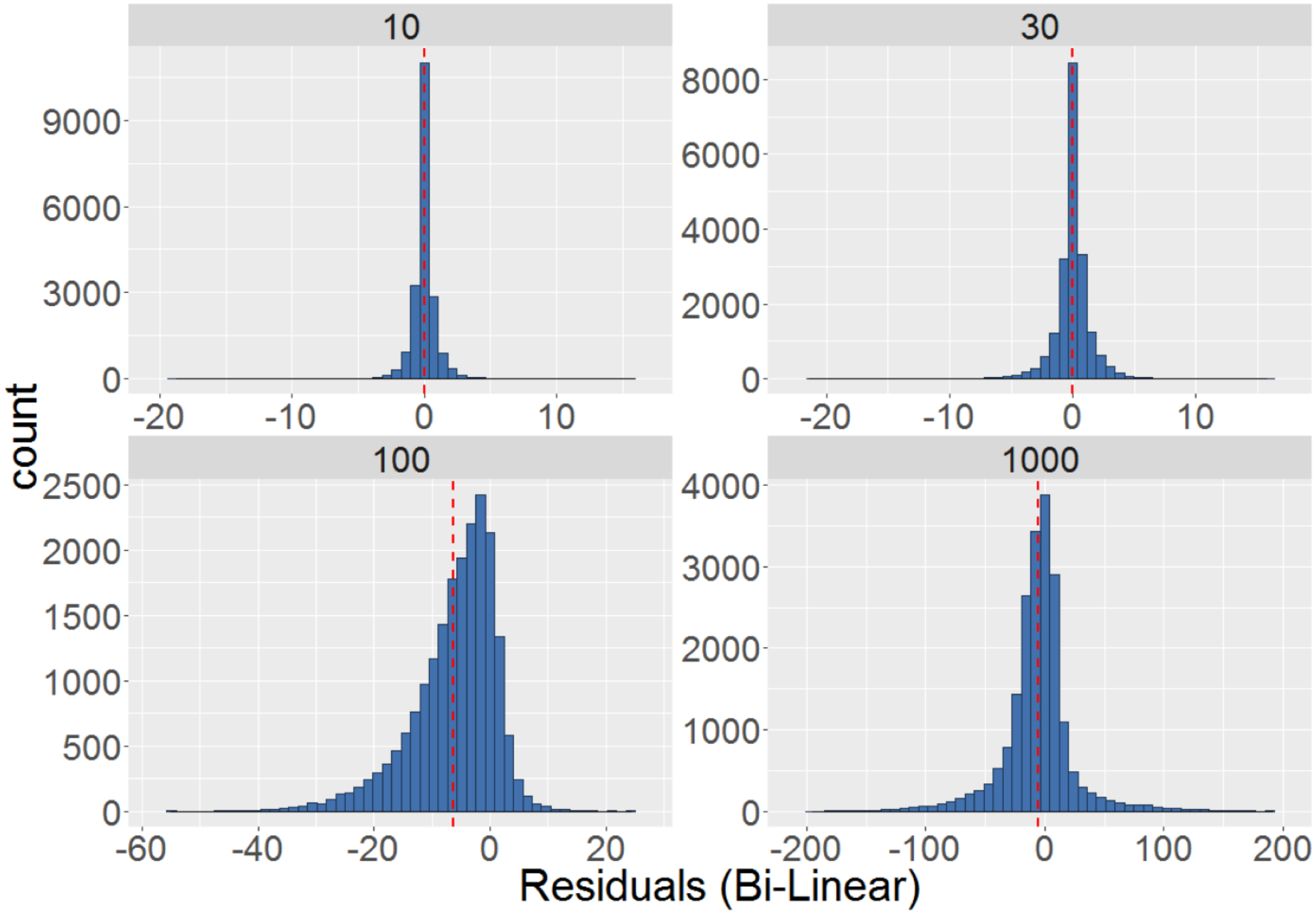
	Slope (°)		Roughness (m)		DEM size (Km²)
	Mean	STD	Mean	STD	
Washington	15.29	14.39	8.24	7.92	4533.35
Colorado	12.31	10.35	5.68	4.73	2493.29
North Carolina	11.01	9.11	4.87	3.97	7786.72
Nebraska	5.07	5.45	2.02	1.65	4709.26
Texas	2.44	3.03	1.09	1.13	5475.28
Louisiana	0.92	1.53	0.35	0.44	5307.17

Data Sets and Study Areas

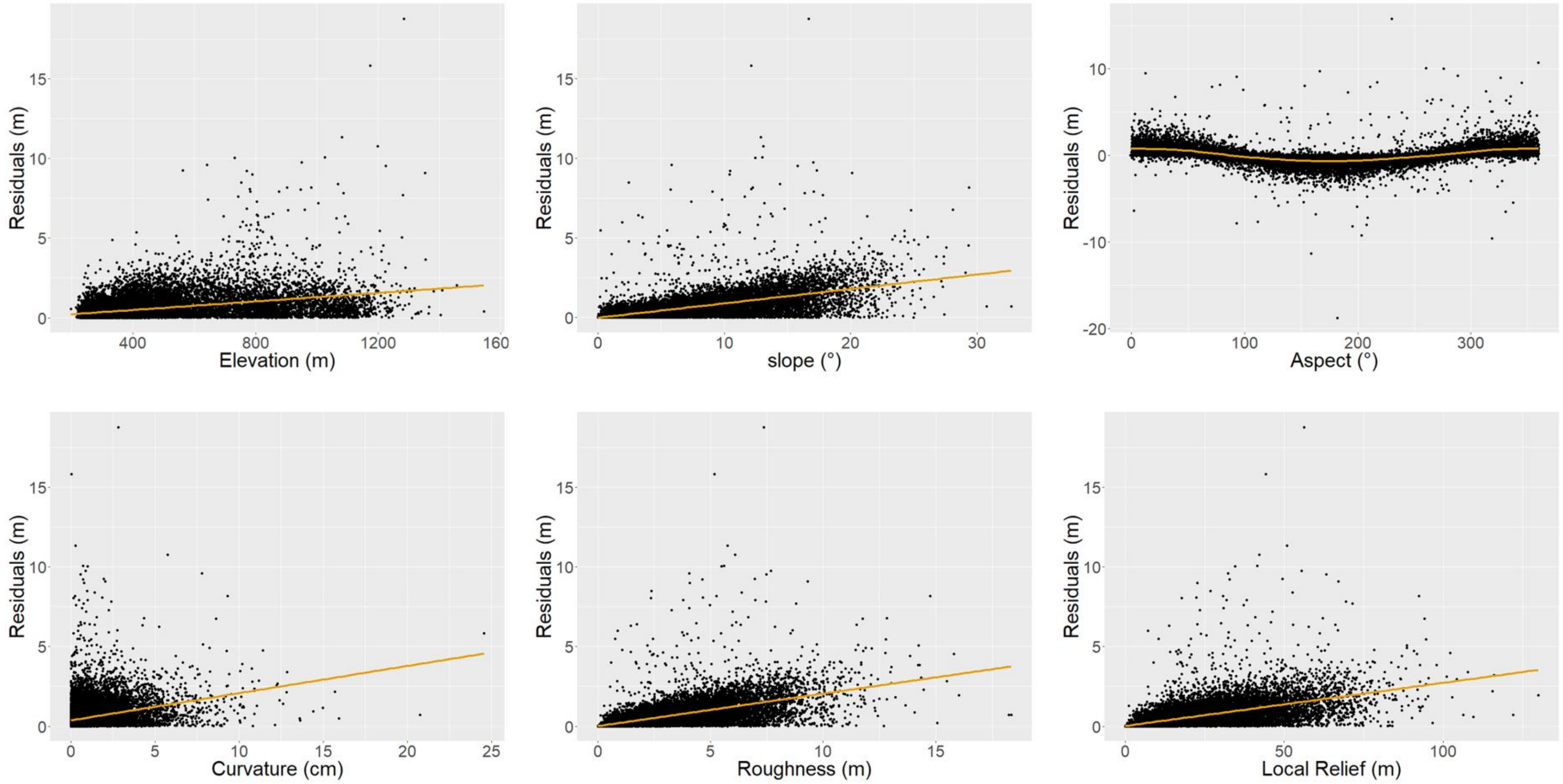


Elevation Estimation (Analysis of Residuals)





Elevation Estimation (Analysis of Residuals)



Variable	Elevation (m)	Slope (°)	Aspect (°)	Curvature (cm)	Roughness (m)	Local relief (m)
Correlation	0.395	0.617	0.000	0.309	0.612	0.576
P-values	0.00	0.00	0.96	0.00	0.00	0.00

RMSE Values (sq. m.) for Different Methods at Different Resolutions

WASHINGTON	10 m	30 m	100 m	1000 m
Linear3	0.69	1.35	15.71	63.74
Bilinear4	0.68	1.32	15.70	63.17
WtdAverage4	0.71	1.46	15.76	63.93
Biquadratic9	0.67	1.22	15.74	63.32
Bicubic16	0.66	1.18	15.70	61.36

COLORADO	10 m	30 m	100 m	1000 m
Linear3	0.37	1.01	7.82	38.64
Bilinear4	0.37	1.01	7.8	38.44
WtdAverage4	0.4	1.11	7.87	38.86
Biquadratic9	0.35	0.93	7.52	38.35
Bicubic16	0.35	0.89	7.53	37.63

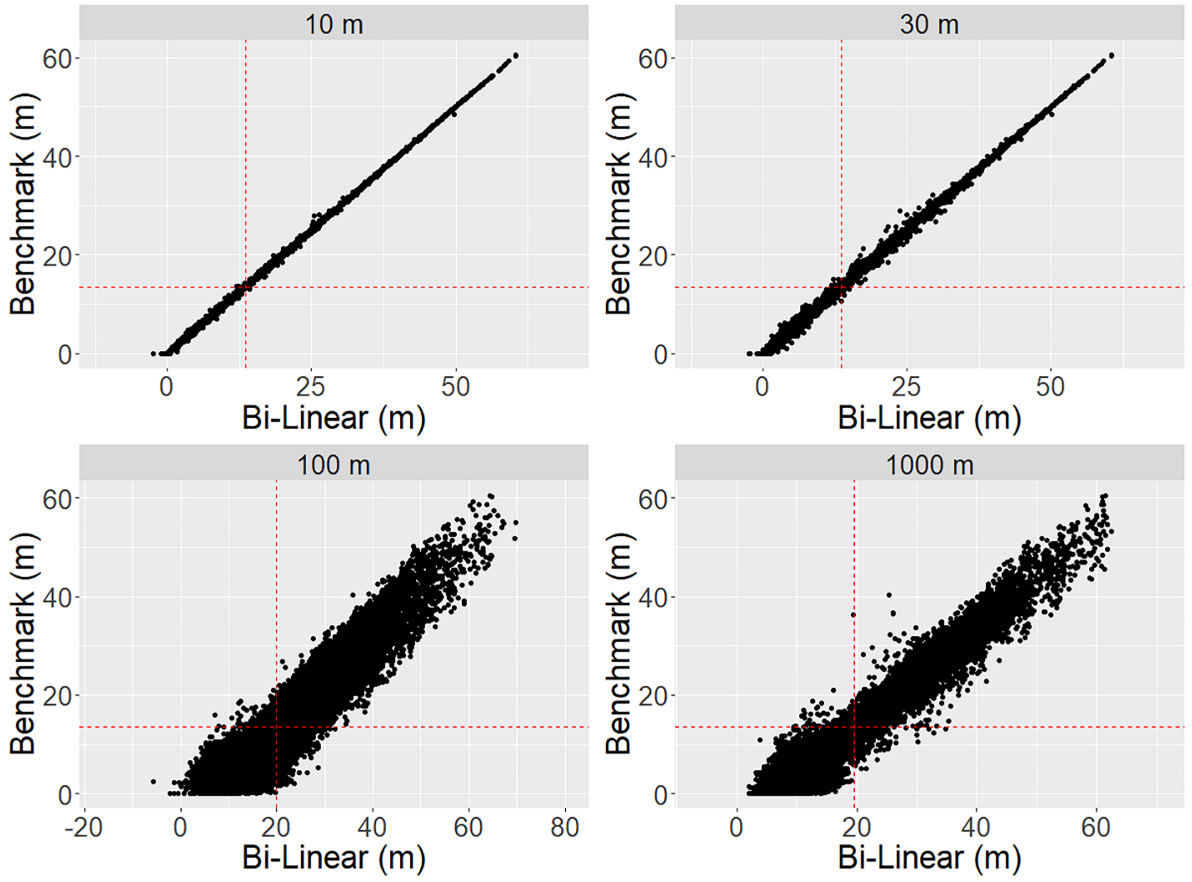
NORTH CAROLINA	10 m	30 m	100 m	1000 m
Linear3	0.91	1.43	9.6	30.03
Bilinear4	0.91	1.42	9.59	29.84
WtdAverage4	0.92	1.48	9.64	30.23
Biquadratic9	0.89	1.31	9.36	29.61
Bicubic16	0.90	1.29	9.38	29.1

NEBRASKA	10 m	30 m	100 m	1000 m
Linear3	0.23	0.74	3.61	8.05
Bilinear4	0.23	0.73	3.61	8.01
WtdAverage4	0.24	0.75	3.62	8.01
Biquadratic9	0.21	0.66	3.51	7.68
Bicubic16	0.2	0.64	3.51	7.73

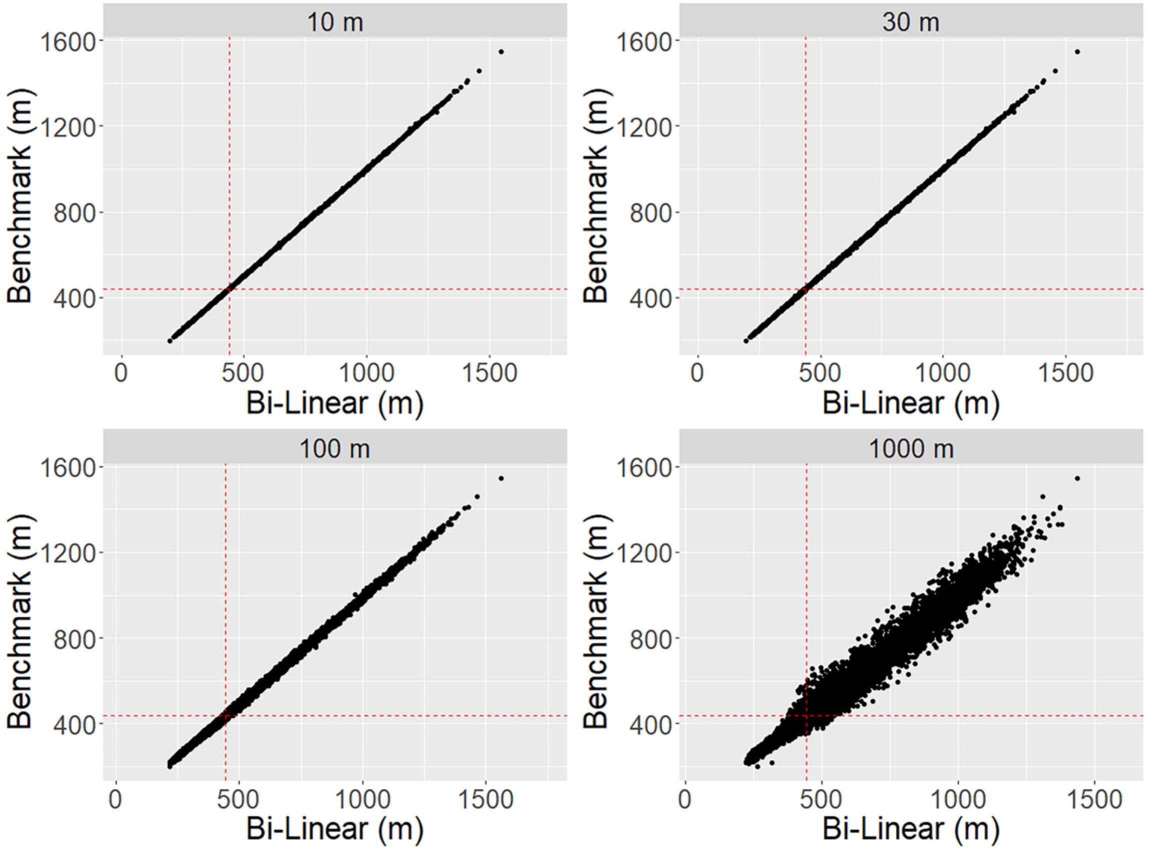
TEXAS	10 m	30 m	100 m	1000 m
Linear3	0.2	0.43	3.85	7.67
Bilinear4	0.19	0.42	3.85	7.64
WtdAverage4	0.2	0.44	3.86	7.68
Biquadratic9	0.19	0.4	3.86	7.57
Bicubic16	0.19	0.39	3.85	7.51

LOUISIANA	10 m	30 m	100 m	1000 m
Linear3	0.13	0.29	7.77	6.78
Bilinear4	0.13	0.28	7.77	6.77
WtdAverage4	0.13	0.29	7.77	6.76
Biquadratic9	0.12	0.28	7.85	6.87
Bicubic16	0.12	0.27	7.83	6.83

RMSE Values (sq. m.) for Different Methods at Different Resolutions

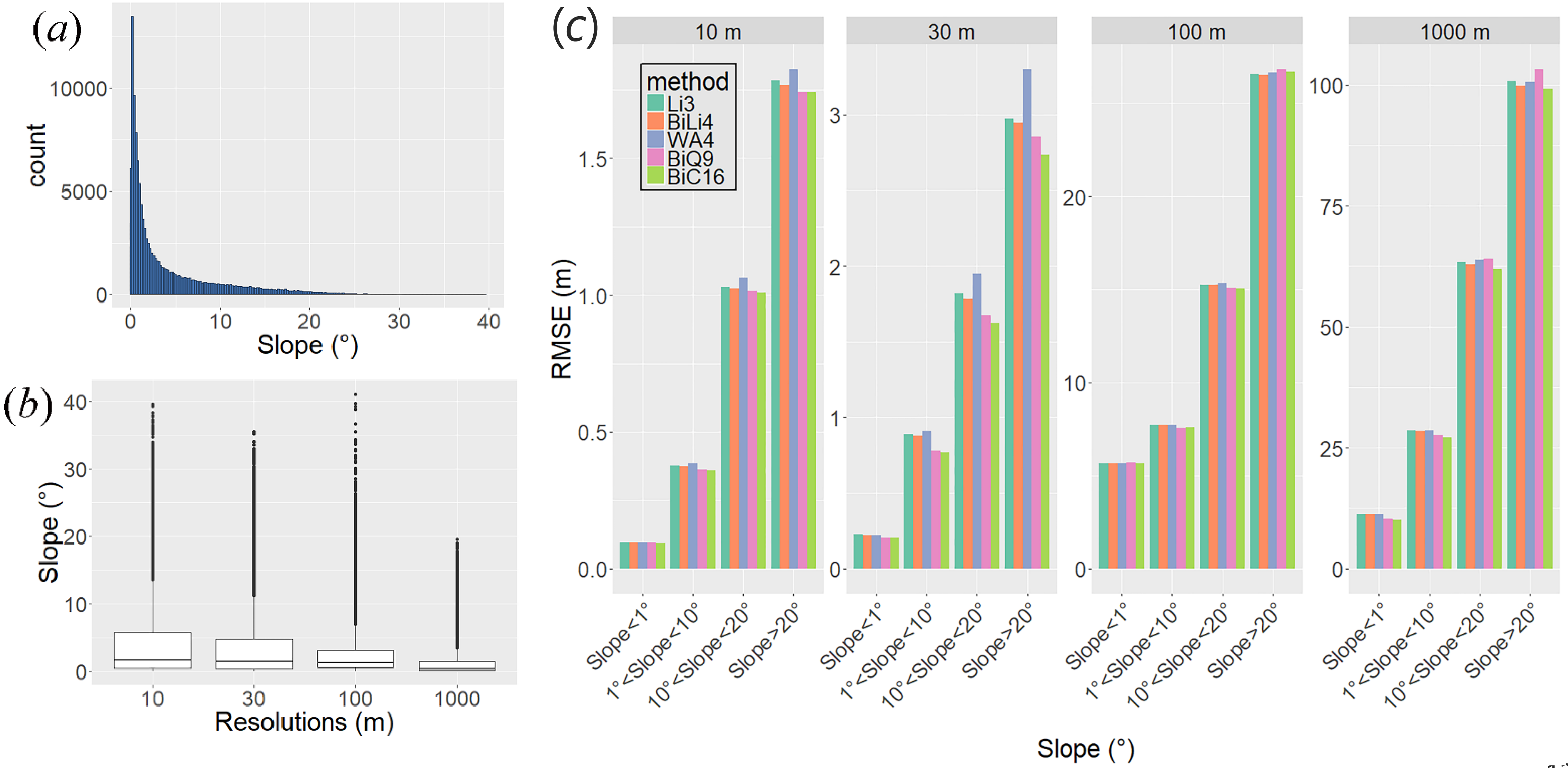


Louisiana



North Carolina

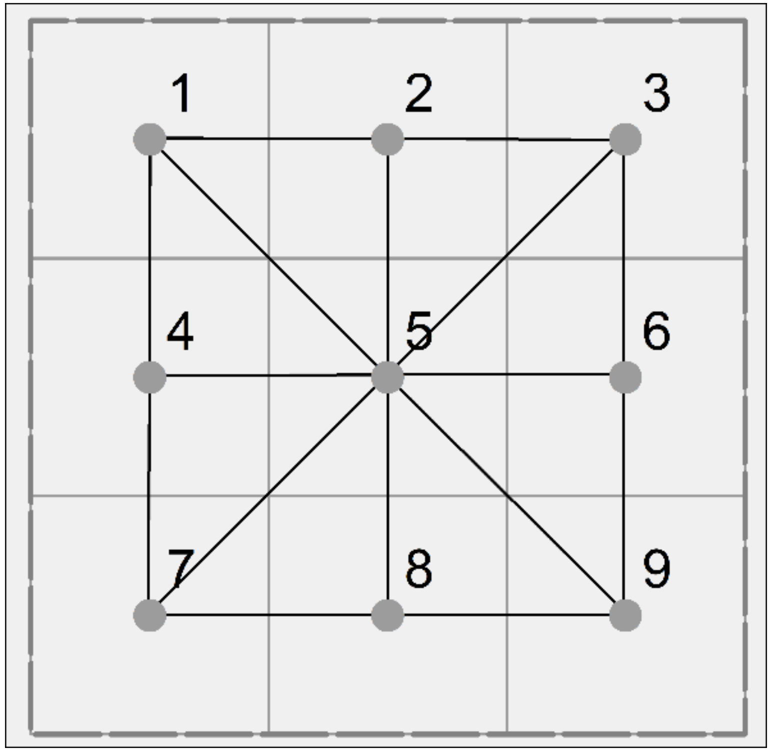
RMSE Values (sq. m.) for Different Methods at Different Resolutions



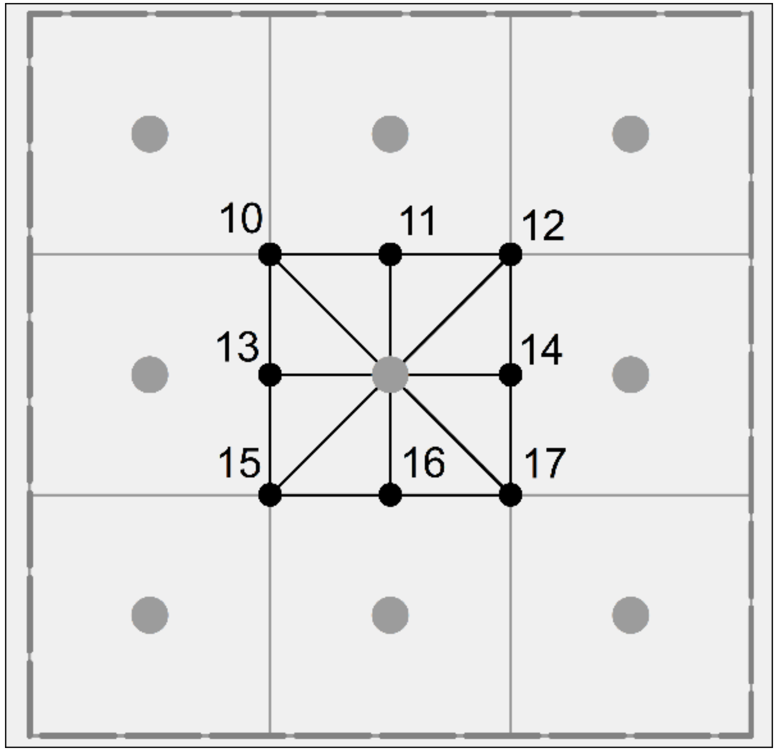
Processing Time Comparison

	Li3	BiLi4	WA4	BiQ9	BiC16
Processing time for 20,000 sample points (seconds)	0.64	0.79	0.62	1.19	1.96

Surface Area Calculations



Jenness Method

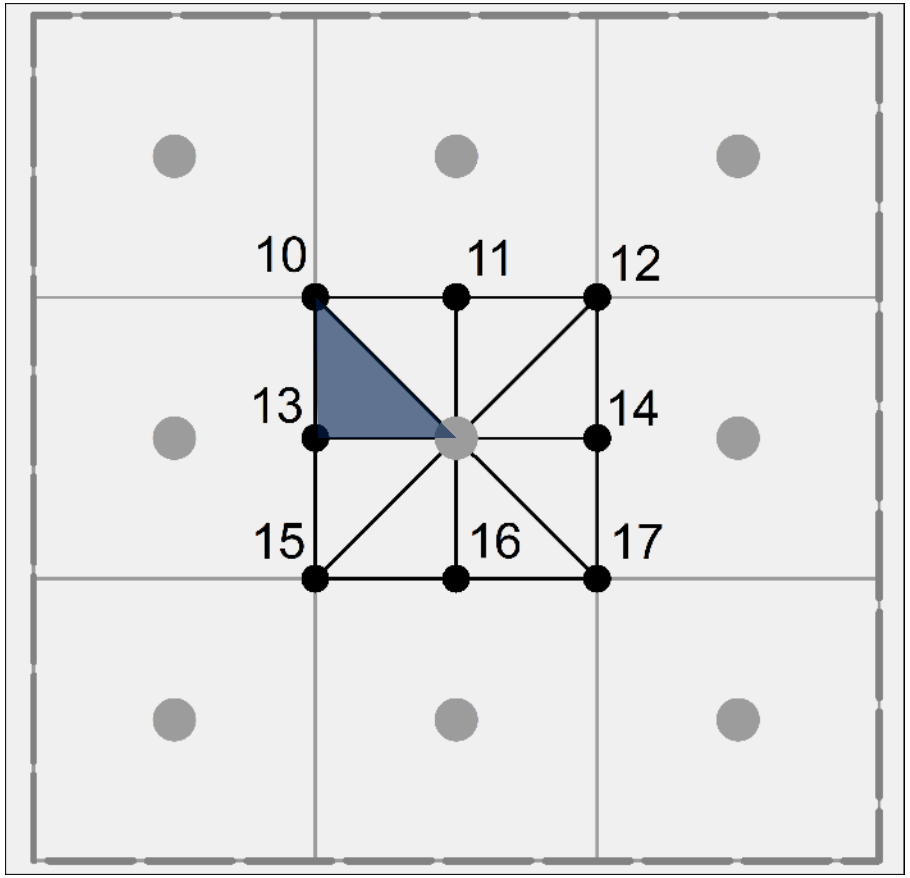


Modified Method

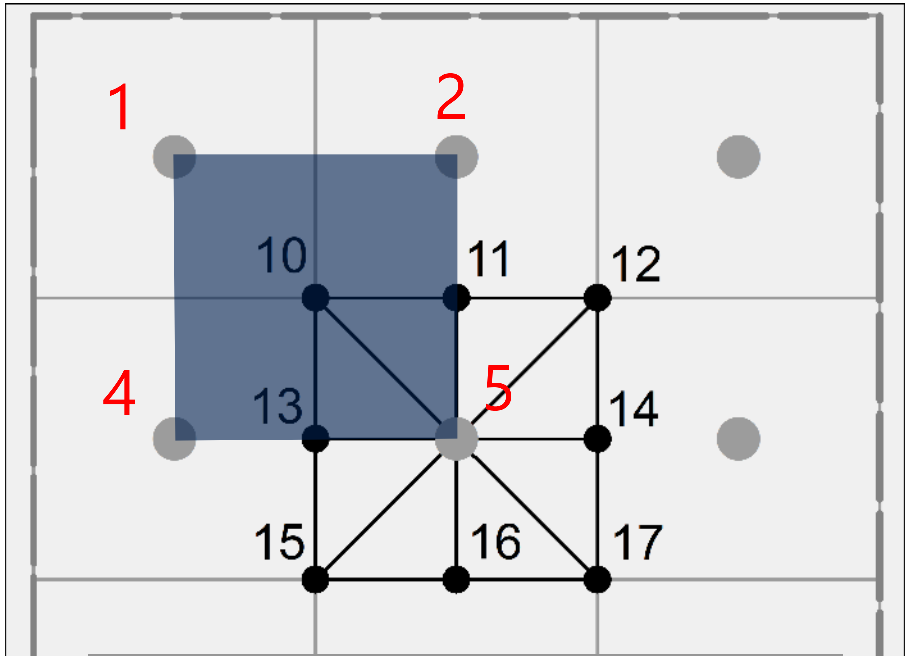
Jenness (2004)

Interpolation Methods

The modified Jenness method is tailored to each interpolation method. For example...

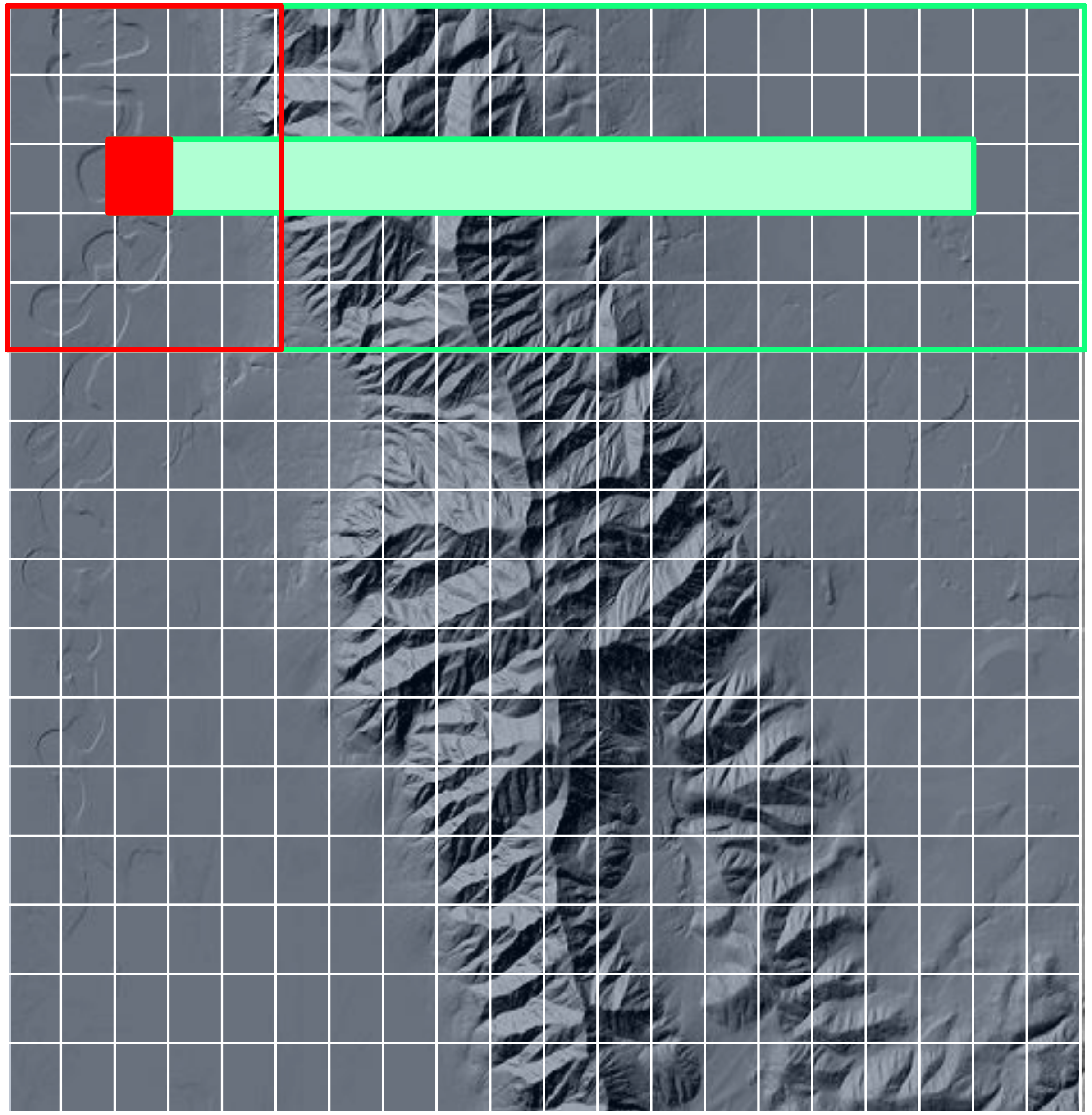


For the Bilinear Interpolation (4-pixel neighborhood), points 10, and13 are interpolated from the nearest four pixels (1,2,4,5).

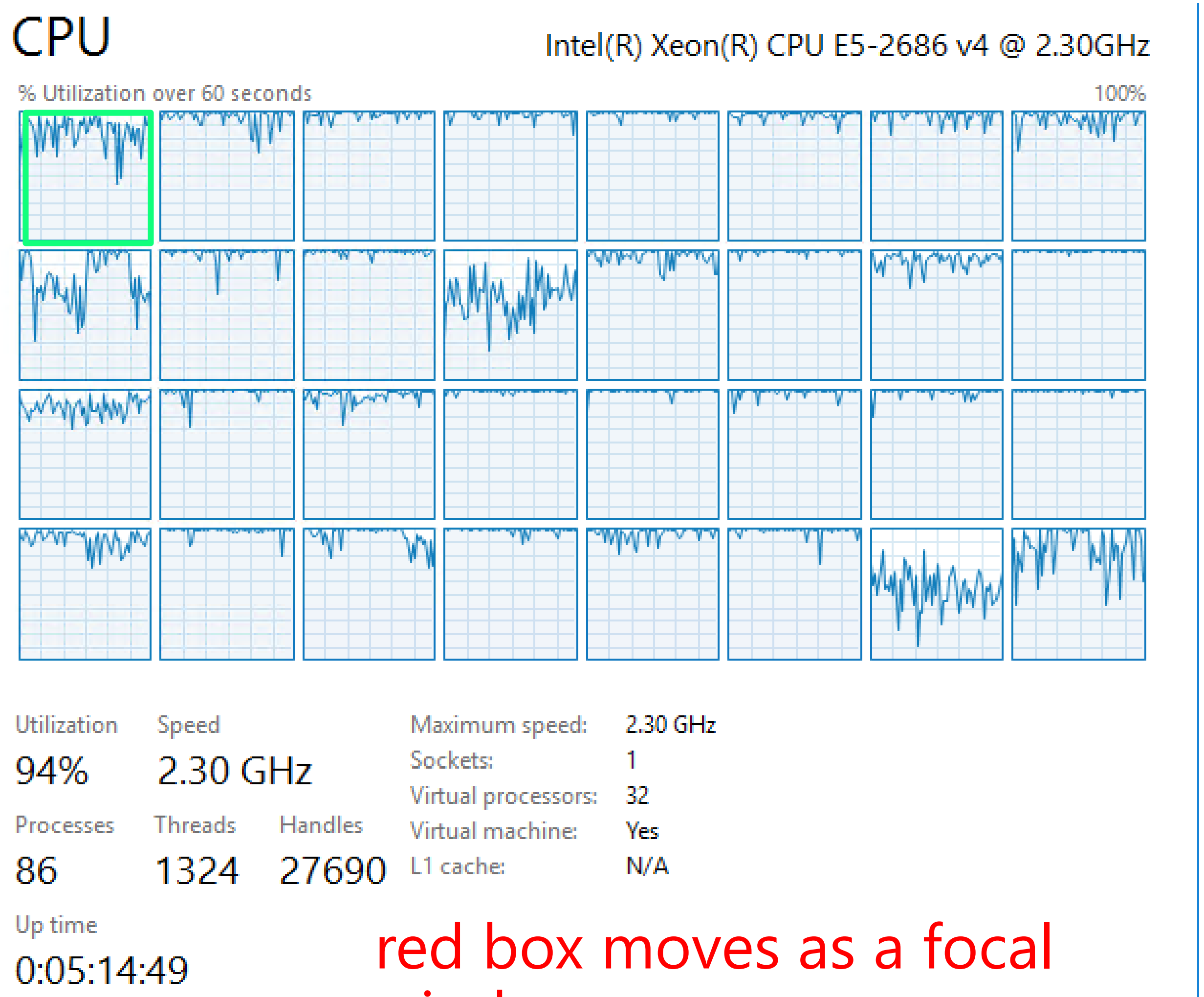


Bilinear 4 pixels:
$z = a_0 + a_1 x + a_2 y + a_3 x y$

Surface Area Calculations (Workflow and Processing)



Amazon Web Services (AWS) virtual server with 32 CPUs and 224 GB of RAM



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Summary Statistics of Surface Area Rasters for North Carolina

Intro
Elevation
Area
Summary

10 m	Mean Area Sq. m.	Std. Dev. Sq. m.	Sum Sq. km.
Benchmark	91.076	6.0618	8,374.753
Planar	87.259	0.000	8,023.207
Slope	90.284	4.926	8,301.949
Jenness	90.525	5.107	8,324.131
Linear3	90.525	5.187	8,324.136
Bilinear4	90.494	5.115	8,321.188
Wtd Average9	89.043	2.852	8,187.846
Biquadratic 9	90.402	5.066	8,312.787
Bicubic16	90.543	5.274	8,325.752

1000 m	Mean Area Sq. m.	Std. Dev. Sq. m.	Sum Sq. km.
Benchmark	712,923.750	10,346.761	7,575.528
Planar	706,837.062	0.000	7,510.850
Slope	707,758.000	2,225.832	7,520.636
Jenness	708,786.687	3,850.350	7,531.567
Linear3	708,787.812	4,185.199	7,531.579
Bilinear4	708,607.375	3,710.965	7,529.662
Wtd Average9	708,072.562	2,844.051	7,523.979
Biquadratic 9	708,157.000	2,914.196	7,524.876
Bicubic16	708,754.750	4,091.762	7,531.228

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RMSE Values (sq. m.) for Different Methods at Different Resolutions

Intro
Elevation
Area
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WASHINGTON	10 m	30 m	100 m	1000 m
Planar	13.695	104.784	790.141	43,265.816
Slope	4.297	34.359	394.108	29,894.168
Jenness	4.032	29.195	375.898	21,739.666
Linear3	3.854	27.765	388.559	22,343.145
Bilinear4	3.939	28.785	381.837	22,961.992
WtdAverage9	7.149	55.526	516.876	29,095.031
Biquadratic9	3.969	30.074	386.471	26,272.572
Bicubic16	3.693	26.118	385.719	22,067.41

COLORADO	10 m	30 m	100 m	1000 m
Planar	8.298	61.614	457.065	20,039.174
Slope	2.829	21.959	220.494	14,871.395
Jenness	2.507	17.682	193.281	11,866.118
Linear3	2.387	17.086	191.879	11,885.051
Bilinear4	2.464	17.711	195.622	12,284.397
WtdAverage9	4.526	33.634	296.526	14,807.516
Biquadratic9	2.537	19.146	205.202	13,521.696
Bicubic16	2.270	16.372	187.988	11,902.85

NORTH CAROLINA	10 m	30 m	100 m	1000 m
Planar	7.163	53.960	380.230	12,003.862
Slope	2.225	20.581	235.759	10,370.065
Jenness	1.924	15.043	207.241	8,652.469
Linear3	1.866	14.872	206.327	8,634.967
Bilinear4	1.922	15.455	210.426	8,899.853
WtdAverage9	3.992	30.097	277.748	9,802.203
Biquadratic9	2.016	17.242	220.189	9,660.688
Bicubic16	1.810	13.958	202.475	8,655.975

NEBRASKA	10 m	30 m	100 m	1000 m
Planar	2.773	16.372	78.373	639.683
Slope	1.372	11.447	70.379	605.736
Jenness	1.141	8.750	66.390	569.497
Linear3	1.064	8.593	66.364	569.904
Bilinear4	1.127	9.035	66.967	575.486
WtdAverage9	1.769	11.608	71.273	595.990
Biquadratic9	1.181	9.941	68.526	591.068
Bicubic16	0.969	8.178	65.944	569.425

RMSE Values (sq. m.) for Different Methods at Different Resolutions

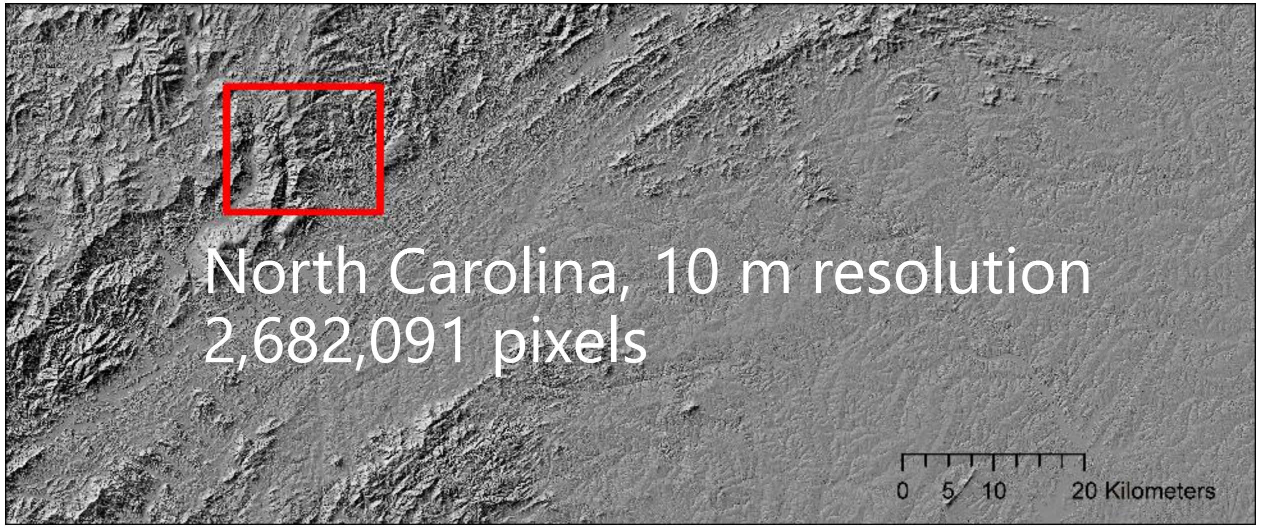
Intro
Elevation
Area
Summary

TEXAS	10 m	30 m	100 m	1000 m
Planar	1.987	11.763	65.334	1,029.190
Slope	1.020	6.767	49.179	938.384
Jenness	0.886	5.680	45.096	851.475
Linear3	0.824	5.348	44.206	844.650
Bilinear4	0.872	5.655	45.209	862.605
WtdAverage9	1.276	7.855	53.141	913.090
Biquadratic9	0.898	5.947	46.397	899.804
Bicubic16	0.782	5.137	43.096	848.091

LOUISIANA	10 m	30 m	100 m	1000 m
Planar	0.5830	2.674	8.718	42.616
Slope	0.4020	2.256	8.453	39.471
Jenness	0.330	1.867	9.445	36.458
Linear3	0.318	1.837	9.911	36.731
Bilinear4	0.333	1.915	9.360	37.029
WtdAverage9	0.422	2.147	8.917	38.817
Biquadratic9	0.355	2.061	8.770	38.123
Bicubic16	0.303	1.828	9.778	36.420

Processing Time Comparison

	Slope	Jenness	Linear3	Bilinear4	WtdAverage9	Biquadratic9	Bicubic16
Processing time in seconds	5.59	25.03	52.21	53.34	41.34	46.62	116.49
Relative processing time	X	4.47X	9.30X	9.54X	7.39X	8.33X	20.83X
Relative RMSE	1.27Y	1.12Y	1.06Y	1.10Y	2.49Y	1.14Y	Y



The Linear and Jenness methods balance improvement in accuracy with faster processing speed

Summary

Cross-scale analysis of elevation and area estimates across resolutions shows varying amounts of error and processing speed.

- Error magnitudes vary with DEM resolution and interpolation method and terrain type.
- There is a general increase in the residuals at coarser resolutions.
- RMSE values decrease to varying degrees moving from rough and non-uniform terrain to smooth and uniform terrain.
- Surface-adjustment methods increase the accuracy of measurements. They also increase the processing time.

Summary

Elevation

- Higher order polynomials (bicubic and biquadratic) outperform weighted average, linear, and bilinear methods in rough terrain and at coarse DEM resolutions.
- The biquadratic and bicubic methods had RMSE values that were statistically equivalent in most DEM resolutions.
- At finer resolutions and flat terrain, the method used to estimate elevations matters less or not at all.
- Bicubic has the highest processing time.
- Weighted Average shows highest RMSE and fastest computations.

Summary

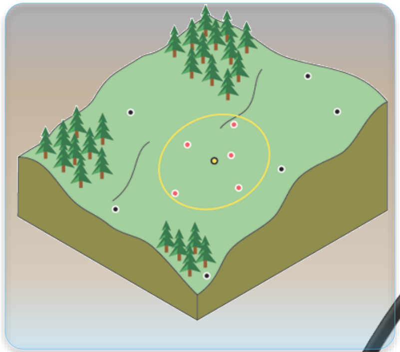
Area

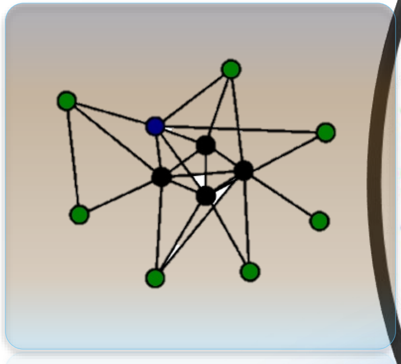
- Bicubic interpolation shows lowest RMSEs at most resolutions.
- Linear, bilinear and Jenness interpolations show the next lowest RMSEs in finer resolutions and they perform better than bicubic in the coarser resolutions.
- Higher order polynomials do not appear to outperform lower order polynomials in every case.
- Weighted average methods show the highest RMSEs.
- Slope method gives the fastest run time .

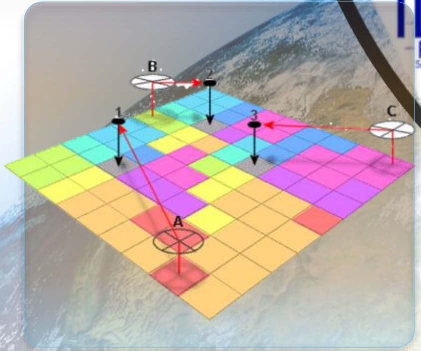
Summary

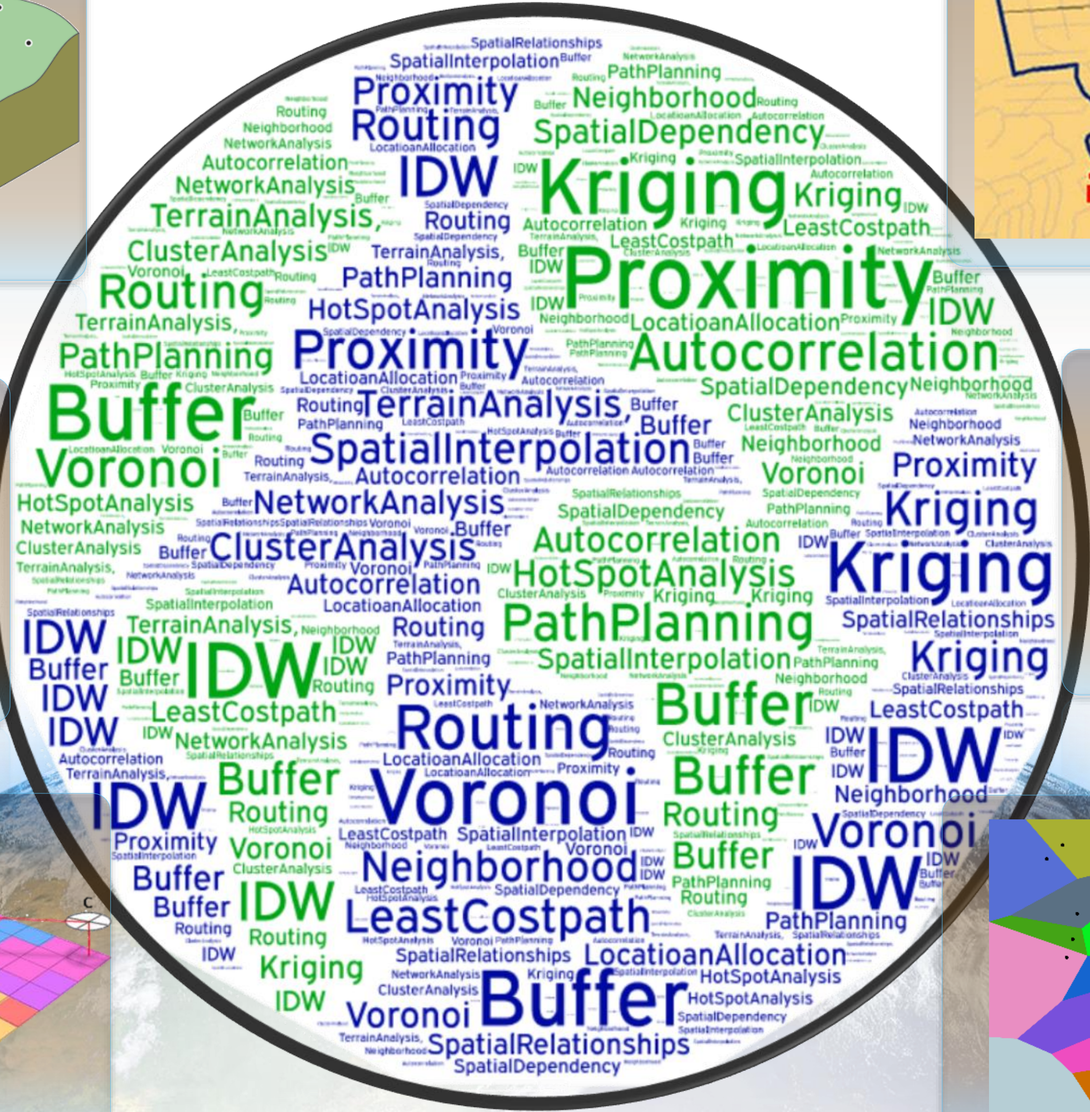
- How to choose?
  - If the ultimate goal is accuracy, choose Bicubic.
  - If the ultimate goal is fast processing, choose Planar (Slope).
  - A balance between accuracy and processing time is achieved with Linear, bilinear or Jenness.

Future Work






B
C
A


SpatialRelationships
SpatialInterpolation
PathPlanning
Proximity
Neighborhood
Routing
SpatialDependency
IDW
Kriging
Kriging
Autocorrelation
LeastCostpath
NetworkAnalysis
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ClusterAnalysis
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PathPlanning
Proximity
HotSpotAnalysis
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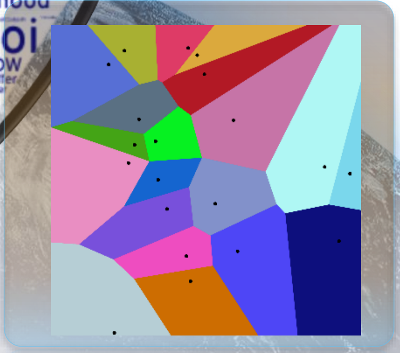
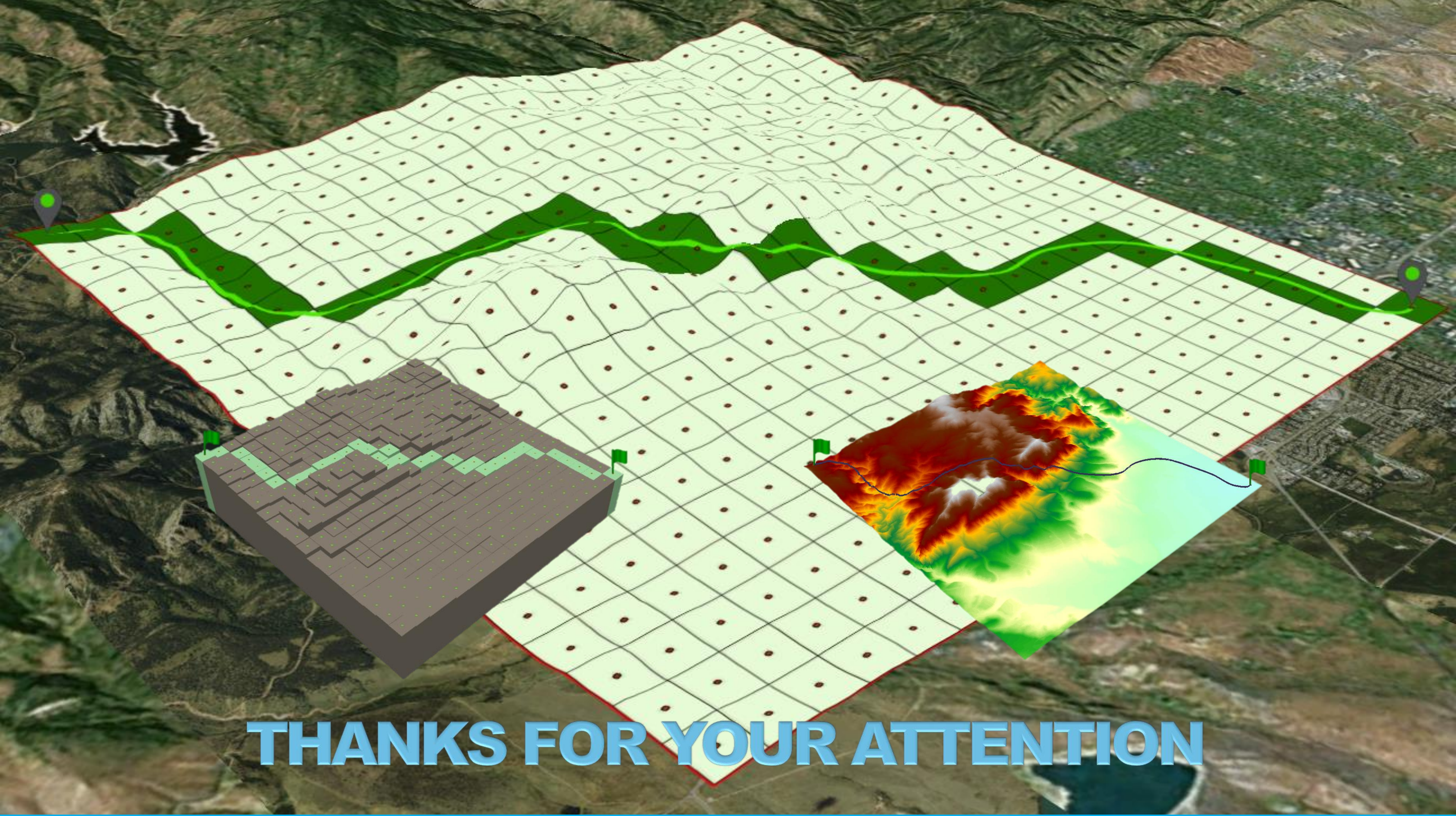
SpatialDependency


A
B
C




THANKS FOR YOUR ATTENTION