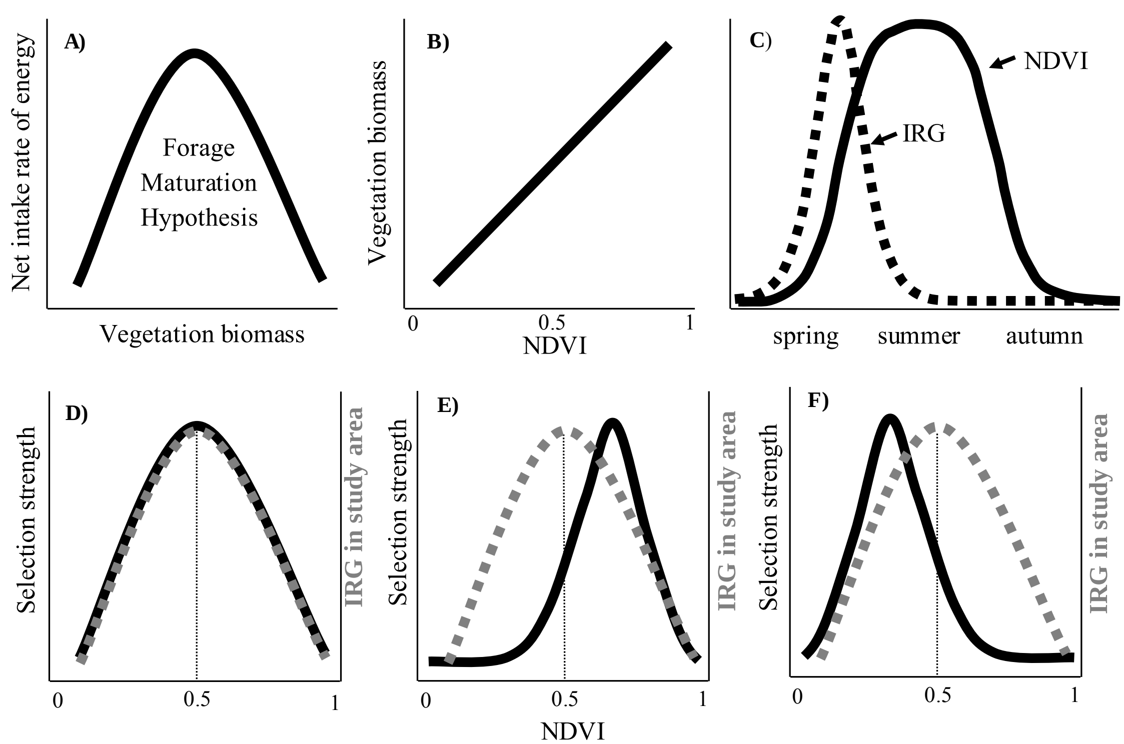
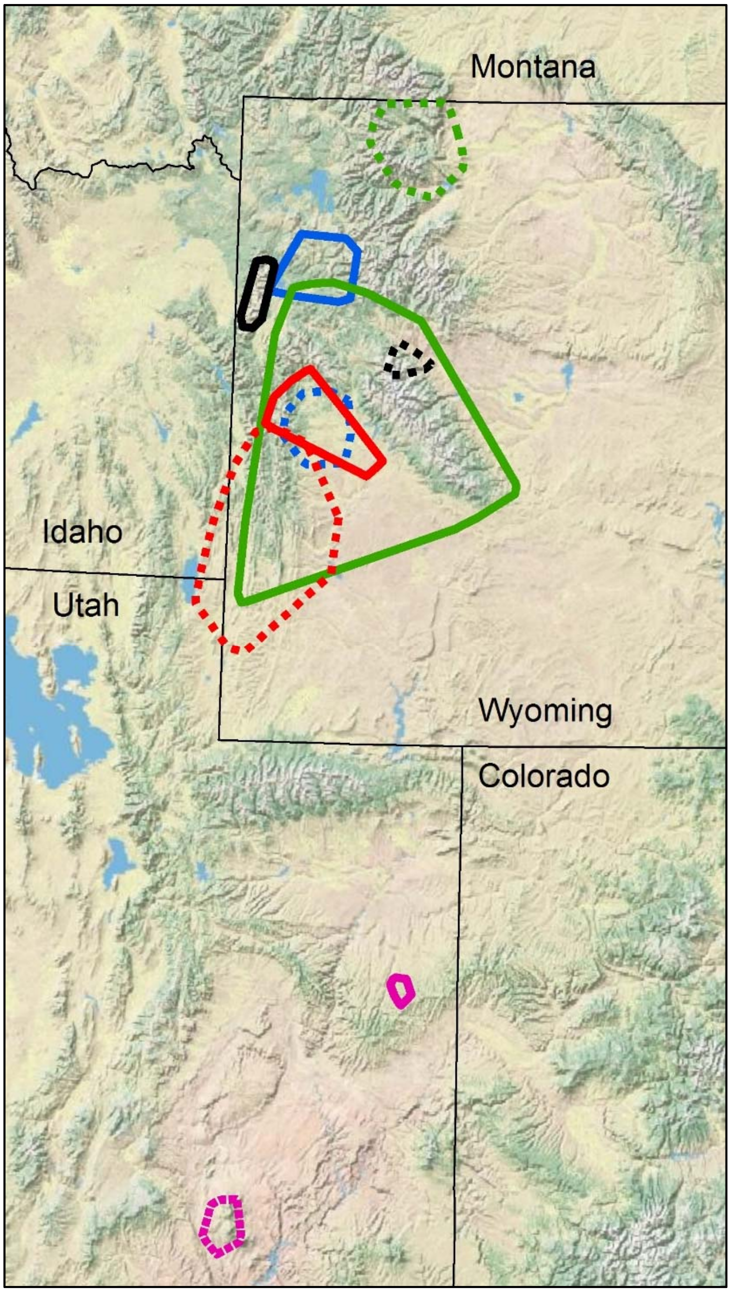
Merkle, J.A., K.L. Monteith, E.O Aikens, M.M. Hayes, K.R. Hershey, A.D. Middleton, B.A. Oates, H. Sawyer, B.M. Scurlock and M.J. Kauffman. XXXX. Large herbivores surf waves of green-up during spring? *Proceedings of the Royal Society B Biological Sciences* XX: XX-XX.

Appendix A. Conceptual chart depicting relationships between the forage maturation hypothesis, vegetation biomass, the Normalized Difference Vegetation Index (NDVI), the Instantaneous Rate of Green-up (IRG), and selection for intermediate values of NDVI. The forage maturation hypothesis (A) purports that herbivores will maximize their net rate of energy intake by eating vegetation at intermediate biomass, because as biomass increases, plants become fibrous and limit the intake rate of energy. NDVI can be a reliable correlate of vegetation biomass (B), and is often used as an index of available green biomass. In most temperate ecosystems, NDVI increases during the spring growing season, then decreases in late summer and autumn (C). The relationship between time (a calendar year) and NDVI can be quantified using a double logistic curve (NDVI in C) fit to a pixel-level, time series of NDVI data. The first derivative of this curve during spring generates the IRG curve (C), which tracks the rate of change of NDVI, reaching its peak during the rapid green-up of vegetation in spring when vegetation is assumed to be at intermediate biomass. The relationship between the strength of selection for a certain habitat patch and NDVI (D, E, F; black lines) is currently unknown. Herbivores that strongly select for IRG will inherently select habitat patches with NDVI values that are half their maximum NDVI (D). Deviations from strong selection for IRG might exist for different taxa or habitats, constituting animals that select the trailing (E, black line) or leading (F, black line) edge of the IRG curve.



Appendix B. Map of study area in western U.S.A. indicating a 95% MCP around each of the 10 study populations: bighorn sheep (black), mule deer (red), elk (green), moose (blue), and bison (pink). State boundaries demarcated by black lines.



Appendix C. Coefficient tables for movement models with most empirical support in each population. Movement models were parameterized by data from two populations each of bighorn sheep, mule deer, elk, moose, and bison in western Wyoming and eastern Utah (totaling 463 individuals) between 2004 and 2014. The movement model was a Step Selection Function, parameterized using conditional logistic regression and general estimating equations. Empirical support was assessed using the Quasi-likelihood under independence criterion (QIC).

Bighorn sheep (Teton range)

Variable	β	SE	*z*	*P*
Meadow	0.885	0.104	8.473	< 0.001
Shrub	0.582	0.104	5.575	< 0.001
Distance	0.328	0.028	11.842	< 0.001
Elevation	3.149	0.205	15.358	< 0.001
Distance to escape terrain	-0.087	0.027	-3.231	0.001
Integrated NDVI	0.014	0.012	1.113	0.266
NDVI	5.698	0.667	8.545	< 0.001
$NDVI^2$	-3.353	0.576	-5.820	< 0.001

Bighorn sheep (Whiskey Basin)

Variable	β	SE	*z*	*P*
Meadow	0.589	0.345	1.706	0.088
Shrub	0.483	0.367	1.317	0.188
Distance	-0.195	0.067	-2.930	0.003
Elevation	1.670	0.532	3.140	0.002
Distance to escape terrain	-0.076	0.128	-0.597	0.550
Integrated NDVI	0.028	0.022	1.255	0.209
IRG	0.776	0.167	4.643	< 0.001

Mule deer (Upper Green River Basin)

Variable	β	SE	*z*	*P*
% tree cover	-0.013	0.006	-2.287	0.022
Distance	0.015	0.034	0.459	0.646
Elevation	0.003	0.460	0.007	0.994
Slope	0.012	0.007	1.867	0.062
Aspect	-0.085	0.087	-0.976	0.329
Integrated NDVI	0.084	0.020	4.251	< 0.001
IRG	1.398	0.336	4.160	< 0.001

Mule deer (SE Wyoming Range)

Variable	β	SE	*z*	*P*
% tree cover	-0.013	0.003	-4.369	< 0.001
Distance	0.082	0.013	6.365	< 0.001
Elevation	-0.235	0.453	-0.519	0.604
Slope	0.031	0.006	5.525	< 0.001
Aspect	-0.641	0.077	-8.297	< 0.001
Integrated NDVI	0.020	0.016	1.310	0.190
NDVI	2.003	0.548	3.656	< 0.001
$NDVI^2$	-1.250	0.497	-2.516	0.012

Elk (S greater Yellowstone ecosystem)

Variable	β	SE	*z*	*P*
% tree cover	-0.012	0.001	-10.229	< 0.001
Distance	0.061	0.018	3.439	< 0.001
Elevation	0.150	0.190	0.792	0.428
Slope	-0.021	0.002	-8.557	< 0.001
Aspect	-0.368	0.026	-14.051	< 0.001
Integrated NDVI	-0.006	0.006	-0.979	0.328
NDVI	0.794	0.119	6.693	< 0.001

Elk (Absaroka)

Variable	β	SE	*z*	*P*
% tree cover	-0.023	0.003	-7.734	< 0.001
Distance	0.068	0.024	2.901	0.004
Elevation	-0.456	0.230	-1.987	0.047
Slope	-0.039	0.003	-11.429	< 0.001
Aspect	-0.089	0.077	-1.155	0.248
Integrated NDVI	0.026	0.016	1.654	0.098
NDVI	0.494	0.241	2.054	0.040

Moose (Buffalo valley)

Variable	β	SE	*z*	*P*
Deciduous forest	0.056	0.234	0.242	0.809
Wetlands	0.167	0.183	0.911	0.362
Distance	0.070	0.030	2.299	0.022
Elevation	-2.444	0.524	-4.660	< 0.001
Slope	-0.027	0.008	-3.202	0.001
Aspect	-0.340	0.080	-4.268	< 0.001
Integrated NDVI	0.018	0.013	1.381	0.167
IRG	0.238	0.150	1.587	0.113

Moose (NE Wyoming Range)

Variable	β	SE	*z*	*P*
Deciduous forest	0.219	0.362	0.605	0.546
Wetlands	0.100	0.111	0.897	0.370
Distance	0.283	0.068	4.158	< 0.001
Elevation	-5.996	1.354	-4.429	< 0.001
Slope	-0.033	0.016	-2.008	0.045
Aspect	-0.075	0.073	-1.022	0.307
Integrated NDVI	0.027	0.024	1.116	0.264
IRG	1.678	0.264	6.366	< 0.001

Bison (Henry mountains)

Variable	β	SE	*z*	*P*
% tree cover	-0.002	0.002	-1.080	0.280
Distance	-0.053	0.023	-2.262	0.024
Elevation	0.424	0.182	2.327	0.020
Slope	-0.085	0.006	-15.052	< 0.001
Aspect	-0.219	0.049	-4.519	< 0.001
Integrated NDVI	0.036	0.010	3.505	< 0.001
NDVI	1.687	0.443	3.808	< 0.001
$NDVI^2$	-1.657	0.487	-3.400	< 0.001

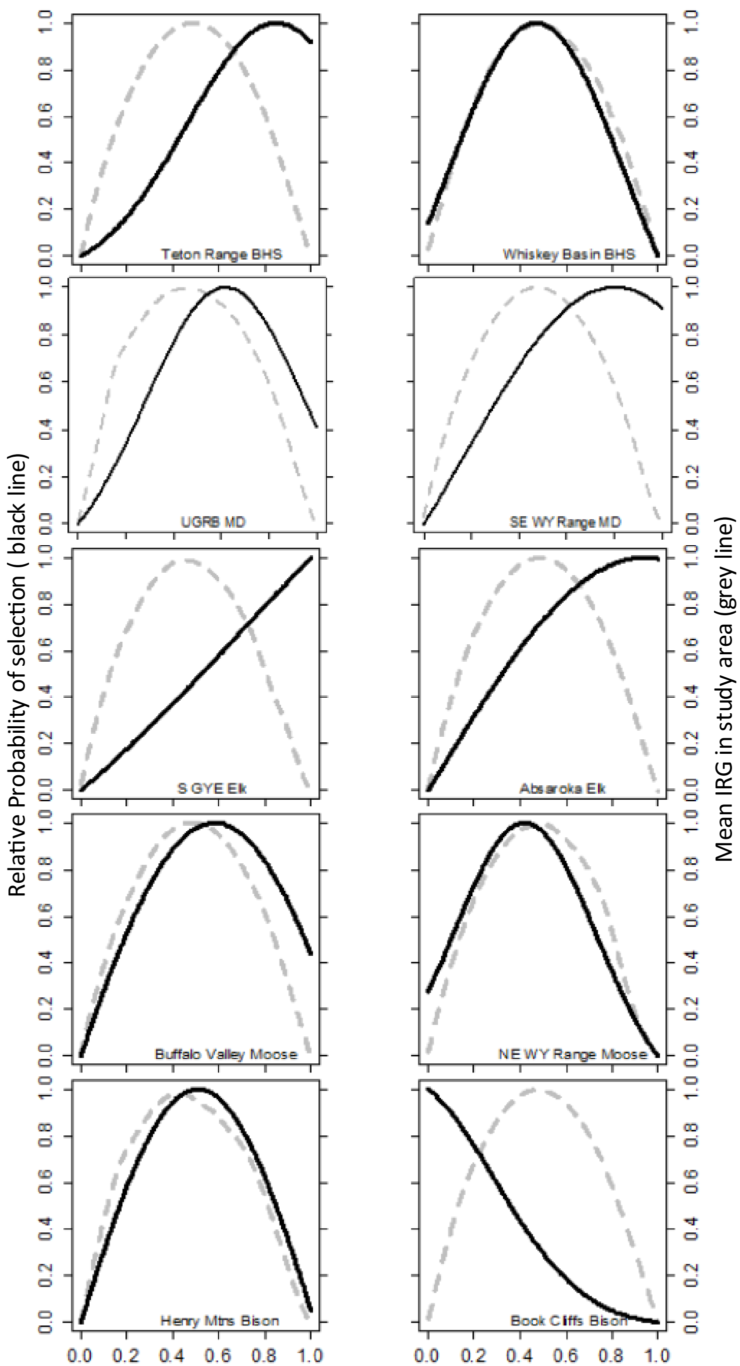
Bison (Book cliffs)

Variable	β	SE	*z*	*P*
% tree cover	-0.074	0.021	-3.538	< 0.001
Distance	0.167	0.030	5.644	< 0.001
Elevation	-0.718	0.254	-2.822	0.005
Slope	-0.113	0.016	-7.256	< 0.001
Aspect	-0.224	0.246	-0.912	0.362
Integrated NDVI	0.270	0.044	6.087	< 0.001
NDVI	-0.711	1.635	-0.435	0.664
$NDVI^2$	-3.255	0.540	-6.027	< 0.001

Appendix D. Mean annual green-up period that individuals were exposed to for two populations each of bighorn sheep, mule deer, elk, moose, and bison in western Wyoming and eastern Utah (totaling 463 individuals) between 2004 and 2014. We defined the green-up period for each used pixel in each year of investigation by identifying the Julian day of the start and end of spring, calculated as the minimum and maximum of the first and second, second derivatives, respectively, of a fitted double logistic curve to the NDVI time series. We calculated the proportion of each population that was migratory by plotting each individual-year movement trajectories and net squared displacement over time, and manually identifying whether there was distinct summer and winter ranges [1, 2].

Species	Population	Proportion migratory	Start date of green-up	Duration of green-up
Bighorn sheep				
	Teton Range	0.02	1 June	64
	Whiskey Basin	0.25	28 April	55
Mule deer				
	Upper Green River Basin	1.00	15 March	110
	SE Wyoming Range	0.96	12 March	112
Elk				
	S Greater Yellowstone	0.72	29 March	91
	Absaroka mountains	0.49	11 March	127
Moose				
	Buffalo Valley	0.81	29 April	48
	NE Wyoming Range	0.30	23 April	64
Bison				
	Henry Mountains	0.52	22 March	143
	Book Cliffs	0.50	8 March	84

Appendix E. Relationship between mean Normalized Difference Vegetation Index (NDVI) and mean Instantaneous Rate of Green-up (IRG) within each study area (grey dashed lines), and relationship between mean predicted relative probability of selection (black lines, based on model with NDVI and $NDVI^2$) of a habitat patch and its NDVI value for two populations each of elk, mule deer (MD), bighorn sheep (BHS), moose, and bison in western Wyoming and eastern Utah between 2004 and 2014. Probability of selection was based on predicted values of a Step Selection Function parameterized with GPS collar data in each population.



Appendix F. Relative empirical support for four movement models of selection for habitat patches by large herbivores during the green-up season. Movement models were parameterized by data from two populations each of bighorn sheep, mule deer, elk, moose, and bison in western Wyoming and eastern Utah (totaling 463 individuals) between 2004 and 2014. The Base model included variables representing habitat attributes known to influence habitat selection of each species (e.g., cover type, elevation, slope, aspect, distance to escape terrain). All other models included variables from the base model. The models were specified follows: NDVI - included a variable that contains spatially and temporally explicit values of fitted (and scaled) Normalized Difference Vegetation Index (NDVI) curves over time; $NDVI^2$ – included a quadratic form of the NDVI values, where NDVI and $NDVI^2$ was included in the model; and IRG – included the Instantaneous Rate of Green-up calculated as the first derivative of the fitted NDVI curve over time. The movement model was a Step Selection Function parametrized using conditional logistic regression. We calculated robust SE and 95% CI of parameters using generalized estimating equations, because of temporal autocorrelation and a lack of independence within an individual's movements. Support was assessed using the Quasi-likelihood under independence criterion (QIC), and *n* refers to the number of individuals in a population, *n* event refers to the number of movement steps used to fit the model, and K is the number of model parameters.

Pop	Model	QIC	ΔQIC	*n* event	K	Pop	Model	QIC	ΔQIC	*n* event	K
Teton Range bighorn sheep (*n* = 20)						Whiskey Basin bighorn sheep (*n* = 8)					
	$NDVI^2$	9615.3	0.0	1584	8		IRG	1336.1	0.0	211	7
	NDVI	9669.5	54.2	1584	7		$NDVI^2$	1336.8	0.7	211	8
	IRG	9762.6	147.3	1584	7		NDVI	1339.4	3.3	211	7
	Base	9793.4	178.1	1584	6		Base	1339.5	3.4	211	6
Green River Basin mule deer (*n* = 29)						SE Wyoming Range mule deer (*n* = 46)					
	IRG	8580.6	0.0	1366	7		$NDVI^2$	12700.8	0.0	2046	8
	$NDVI^2$	8587.2	6.6	1366	8		NDVI	12707.0	6.2	2046	7
	NDVI	8618.0	37.4	1366	7		IRG	12709.5	8.7	2046	7
	Base	8646.2	65.6	1366	6		Base	12716.9	16.1	2046	6
S Greater Yellowstone elk (*n* = 119)						Absaroka mountains elk (*n* = 88)					
	NDVI	65654.8	0.0	10345	7		NDVI	14724.1	0.0	2371	7
	$NDVI^2$	65656.1	1.3	10345	8		$NDVI^2$	14724.2	0.1	2371	8
	Base	65747.1	92.3	10345	6		Base	14727.5	3.4	2371	6
	IRG	65750.2	95.4	10345	7		IRG	14727.5	3.4	2371	7
Buffalo Valley moose (*n* = 39)						NE Wyoming Range moose (*n* = 64)					
	IRG	7998.6	0.0	1243	8		IRG	8034.3	0.0	1259	8
	Base	7999.6	1.0	1243	7		$NDVI^2$	8067.2	33.0	1259	9
	$NDVI^2$	8001.2	2.6	1243	9		NDVI	8089.7	55.5	1259	8
	NDVI	8002.3	3.7	1243	8		Base	8120.4	86.1	1259	7
Henry Mountains bison (*n* = 46)						Book Cliff bison (*n* = 4)					
	$NDVI^2$	15294.3	0.0	2669	8		$NDVI^2$	848.5	0.0	156	8
	IRG	15302.9	8.6	2669	7		NDVI	851.2	2.7	156	7
	Base	15314.3	20.1	2669	6		Base	854.7	6.1	156	6
	NDVI	15314.6	20.3	2669	7		IRG	855.5	7.0	156	7

Appendix G. Mean (and SD) Spearman rank correlation coefficients of the match between predicted versus withheld observed data based on a 5-folds cross-validation repeated 100 times for the Step Selection Function in each population with the most empirical support. Step Selection Functions were parameterized with data from two populations each of bighorn sheep, mule deer, elk, moose, and bison in western Wyoming and eastern Utah (totaling 463 individuals) between 2004 and 2014. *n* refers to the number of GPS collared individuals in the population. We conducted cross-validation following the methods outlined in Fortin et al. [3] for the use of conditional logistic regression to parametrize Step Selection Functions.

Species	Population	Observed		Random	
		Mean	SD	Mean	SD
Bighorn sheep					
	Teton Range (*n* = 20)	0.88	0.04	-0.05	0.76
	Whiskey Basin (*n* = 8)	0.28	0.15	-0.11	0.46
Mule deer					
	Upper Green River Basin (*n* = 29)	0.33	0.15	-0.18	0.24
	SE Wyoming Range (*n* = 46)	0.78	0.07	-0.22	0.43
Elk					
	S Greater Yellowstone (*n* = 119)	0.93	0.02	-0.11	0.82
	Absaroka mountains (*n* = 88)	0.85	0.05	-0.08	0.61
Moose					
	Buffalo Valley (*n* = 39)	0.53	0.13	-0.03	0.26
	NE Wyoming Range (*n* = 64)	0.60	0.12	-0.02	0.57
Bison					
	Henry Mountains (*n* = 46)	0.36	0.07	-0.75	0.13
	Book Cliffs (*n* = 4)	0.49	0.10	-0.21	0.40

[1] Fryxell, J.M., Greever, J. & Sinclair, A. 1988 Why are migratory ungulates so abundant? *Am. Nat.*, 781-798.
[2] Bunnefeld, N., Börger, L., van Moorter, B., Rolandsen, C.M., Dettki, H., Solberg, E.J. & Ericsson, G. 2011 A model-driven approach to quantify migration patterns: individual, regional and yearly differences. *Journal of Animal Ecology* **80**, 466-476.
[3] Fortin, D., Fortin, M.E., Beyer, H.L., Duchesne, T., Courant, S. & Dancose, K. 2009 Group-size-mediated habitat selection and group fusion-fission dynamics of bison under predation risk. *Ecology* **90**, 2480-2490.