

Insights into the linkages of forest structure dynamics with ecosystem services

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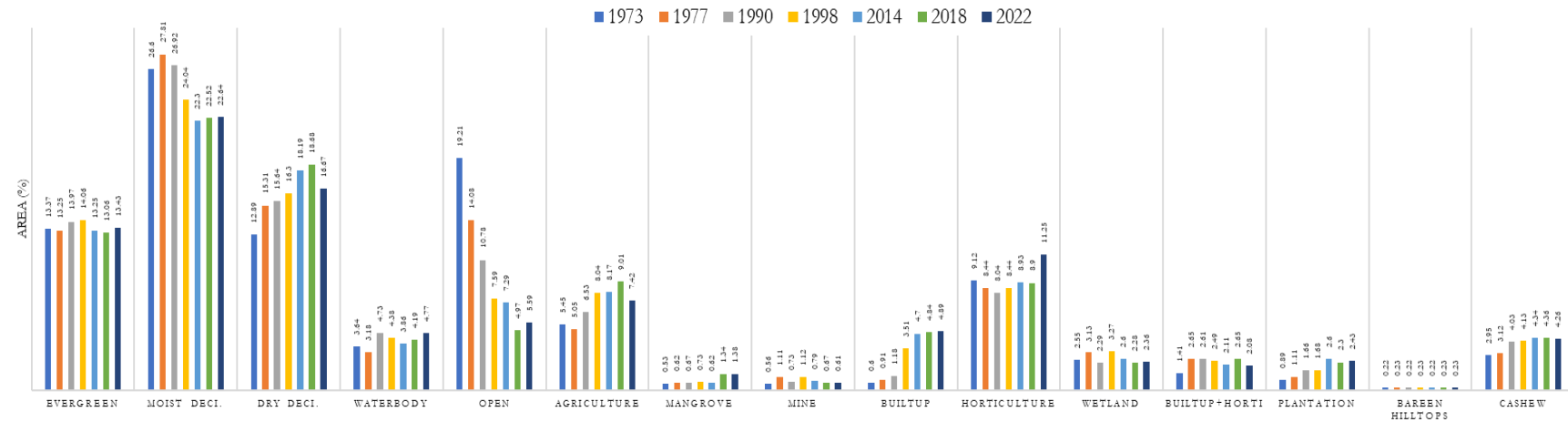
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Supplementary Table S1. The spatial extent of land cover (1973 to 2022) in Goa.

NDVI	1973		1977		1990		1998		2014		2018		2022	
	sq. km	%	sq. km	%	sq. km	%	sq. km	%	sq. km	%	sq. km	%	sq. km	%
Vegetation	2347.43	63.41	2462.97	66.53	2474.76	66.90	2415.74	65.25	2407.03	65.02	2403.36	64.92	2402.92	64.91
Non-vegetation	1354.57	36.59	1239.03	33.47	1224.64	33.10	1286.26	34.75	1294.97	34.98	1298.64	35.08	1299.18	35.09

Supplementary Figure S1. Land use dynamics (1973 to 2022) in Goa.



Supplementary Information

Supplementary Table S2. The spatial extent of land uses (1973 – 2022) in Goa.

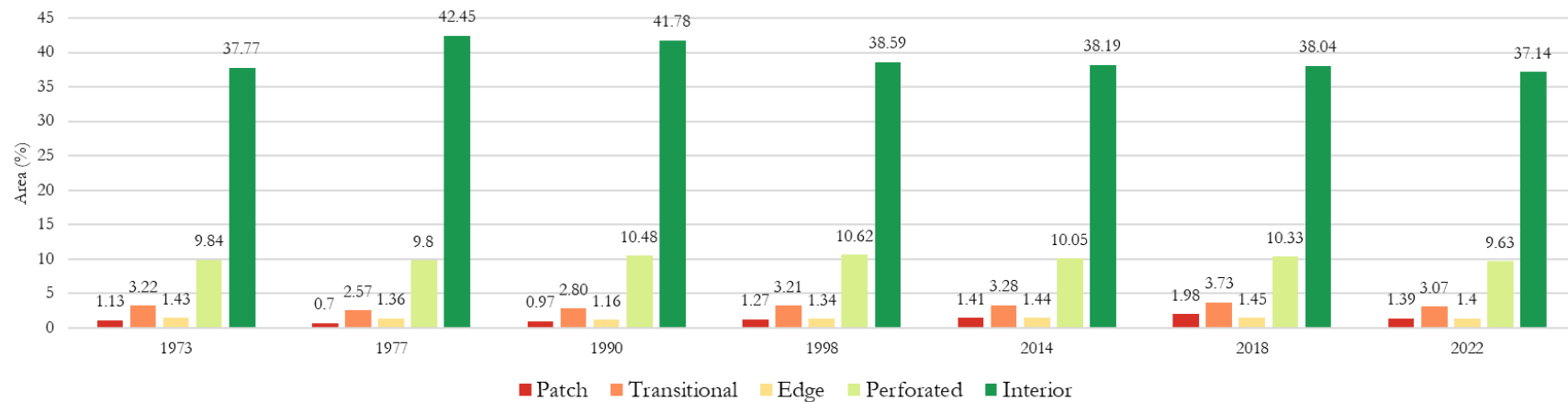
Land use	1973		1977		1990		1998		2014		2018		2022	
	sq. km	%	sq. km	%	sq. km	%	sq. km	%	sq. km	%	sq. km	%	sq. km	%
Evergreen	495.12	13.37	490.6	13.25	516.64	13.96	520.34	14.06	490.67	13.25	483.53	13.06	497.31	13.43
Moist Deciduous	984.79	26.6	1029.43	27.81	995.88	26.9	890.07	24.04	825.62	22.3	833.82	22.52	838.04	22.64
Dry Deciduous/Shrubs	477.03	12.89	566.66	15.31	578.72	15.63	603.5	16.3	673.57	18.19	691.6	18.68	616.99	16.67
Waterbody	134.81	3.64	117.88	3.18	175.12	4.73	162.05	4.38	142.81	3.86	154.99	4.19	176.5	4.77
Open	711.19	19.21	521.33	14.08	401.43	10.84	280.92	7.59	270	7.29	183.9	4.97	207.1	5.59
Agriculture	201.75	5.45	187.06	5.05	241.49	6.52	297.48	8.04	302.54	8.17	333.5	9.01	274.51	7.42
Mangrove	19.73	0.53	22.79	0.62	24.8	0.67	26.89	0.73	22.97	0.62	49.68	1.34	51.16	1.38
Mine	20.6	0.56	41.02	1.11	27.13	0.73	41.47	1.12	29.38	0.79	24.69	0.67	22.45	0.61
Built-up	22.2	0.6	33.86	0.91	43.69	1.18	129.82	3.51	173.99	4.7	179.19	4.84	180.94	4.89
Horticulture	337.63	9.12	312.42	8.44	297.46	8.04	312.59	8.44	330.77	8.93	329.64	8.9	416.39	11.25
Wetland	94.45	2.55	115.87	3.13	84.89	2.29	121.09	3.27	96.16	2.6	84.3	2.28	87.46	2.36
Built-up + Horticulture	52.35	1.41	98.17	2.65	96.4	2.6	92.19	2.49	78.23	2.11	98.16	2.65	77.05	2.08
Forest Plantation	33.13	0.89	41.07	1.11	61.26	1.65	62.35	1.68	96.43	2.6	85.09	2.3	90.03	2.43
Barren hilltops and cliffs	8.18	0.22	8.51	0.23	8.18	0.22	8.5	0.23	8.18	0.22	8.5	0.23	8.47	0.23
Cashew	109.04	2.95	115.33	3.12	148.91	4.02	152.74	4.13	160.68	4.34	161.41	4.36	157.7	4.26

Supplementary Table S3. Predicted Land uses for 2038 considering Business as usual scenario (BAU) and Agent-based Modeling (ABM).

Land use	2038 Business as usual scenario (BAU)		2038 Agent-based Modeling (ABM)	
	sq. km	%	sq. km	%
Evergreen	394.98	10.67	407.86	10.98
Moist Deciduous	823.41	22.24	733.38	19.74
Dry Deciduous/Shrubs	759.55	20.52	618.13	16.64
Waterbody	122.16	3.30	155.56	4.19
Open	190.25	5.14	179.19	4.82
Agriculture	345.74	9.34	247.00	6.65
Mangrove	62.51	1.69	39.25	1.06
Mine	25.79	0.70	31.35	0.84
Built-up	214.51	5.79	234.39	6.31
Horticulture	307.83	8.32	508.71	13.69
Wetland	89.15	2.41	68.67	1.85
Built-up with horticulture	114.69	3.10	130.97	3.52
Forest Plantation	94.62	2.56	194.48	5.23
Barren Hillocks and Cliffs	7.32	0.20	8.18	0.22
Cashew	149.49	4.04	158.45	4.26

Supplementary Table S4. Forest fragmentation indices with description and their ecological implications [1-6].

Fragmentation indices	Details	Ecological Implications
Patch	A discrete area of forest surrounded by non-forest land.	Smaller patches can lead to reduced biodiversity and increased vulnerability to disturbances.
Edge	The boundary between the forest and the surrounding non-forest area.	More susceptible to environmental changes, affecting local microclimates and species distribution.
Transitional	Areas where forest types or conditions are changing due to natural or human-induced factors.	Serve as corridors for species migration but face increased vulnerability due to changing conditions.
Interior	Core areas of larger forest patches, far from the edges.	Intact forests / Interior forests moderate microclimate and are crucial for maintaining biodiversity and sustaining ecosystem services.
Perforated	Forests with numerous small gaps or clearings within a larger forest area.	Increase fragmentation by creating more edges and isolating patches, potentially reducing habitat quality and connectivity.

Supplementary Figure S2. Changes in forest structure from 1973 to 2022 in Goa.


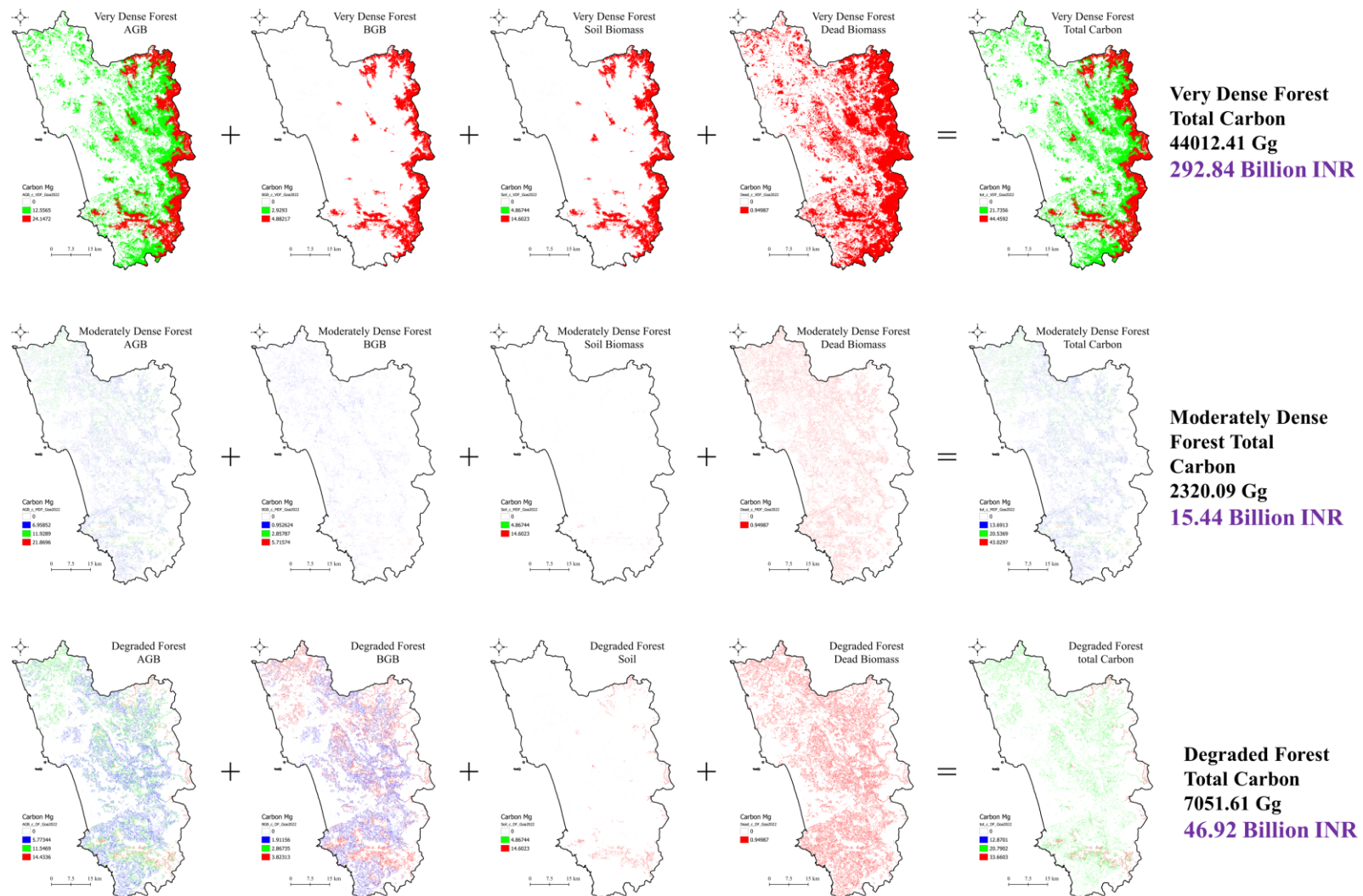
Supplementary Table S5. Condition of forest ecosystems (1973-2022) in Goa.

Forest Fragmentation	1973		1977		1990		1998		2014		2018		2022	
	sq. km	%	sq. km	%	sq. km	%	sq. km	%	sq. km	%	sq. km	%	sq. km	%
Non-forest	1590.53	42.96	1478.52	39.94	1410.84	38.11	1502.95	40.6	1541.71	41.65	1491.09	40.28	1590.22	42.96
Patch	41.8	1.13	25.74	0.7	36.06	0.97	47.05	1.27	52.17	1.41	73.45	1.98	51.55	1.39
Transitional	119.14	3.22	95.25	2.57	103.66	2.8	118.77	3.21	121.6	3.28	137.91	3.73	113.79	3.07
Edge	53.12	1.43	50.38	1.36	42.94	1.16	49.52	1.34	53.22	1.44	53.75	1.45	51.94	1.4
Perforated	364.22	9.84	362.76	9.8	387.8	10.48	393.06	10.62	372.17	10.05	382.5	10.33	356.43	9.63
Interior	1398.38	37.77	1571.47	42.45	1545.58	41.75	1428.6	38.59	1413.67	38.19	1408.31	38.04	1375.06	37.14
Water	134.81	3.64	117.88	3.18	175.12	4.73	162.05	4.38	147.46	3.98	154.99	4.19	163.01	4.4

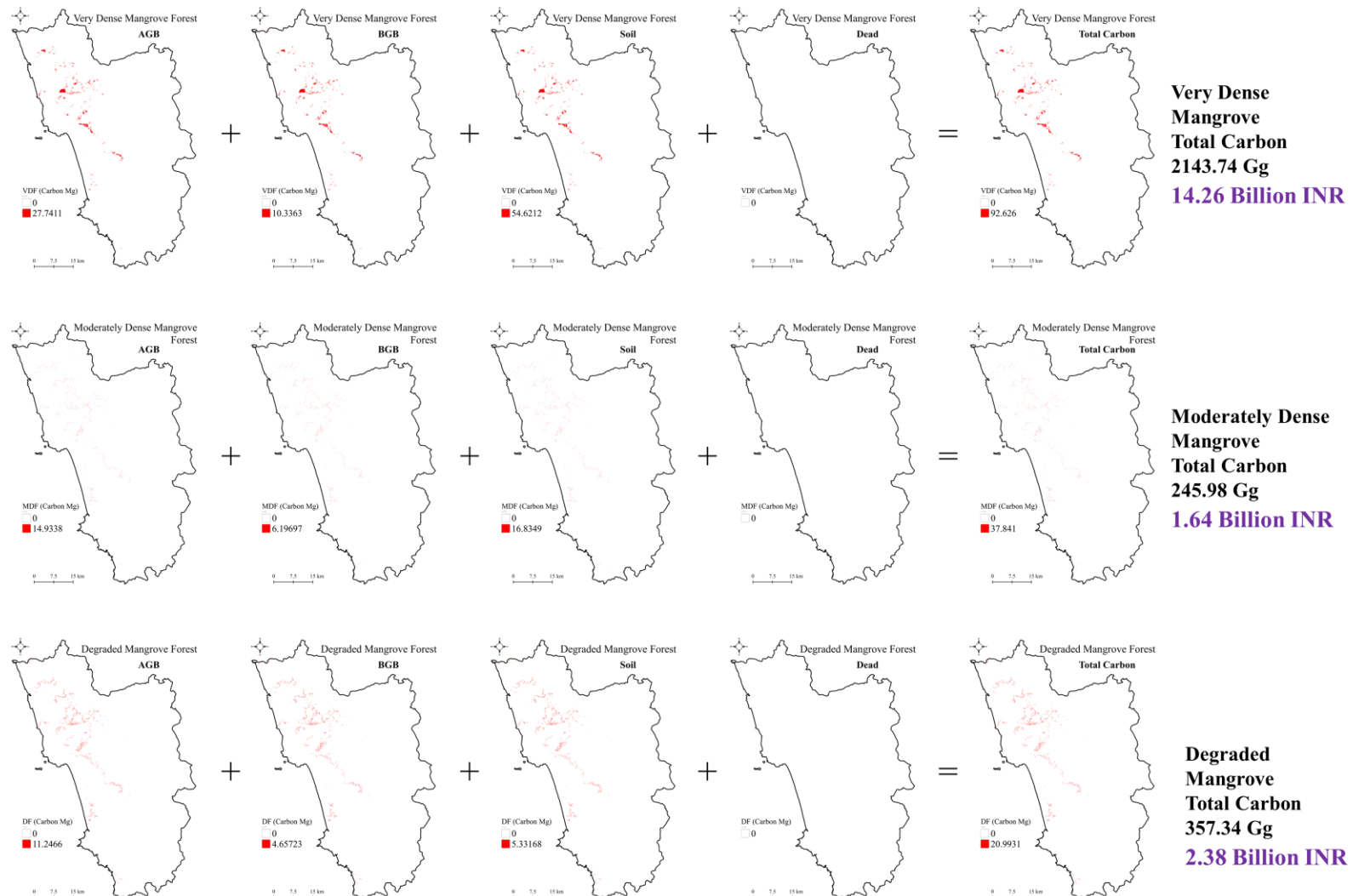
Supplementary Table S6. Carbon storage in the terrestrial forest ecosystems of Goa

Carbon storage	2022 (Gg)	Billion ₹
Forest Density Categories		
Very Dense Forests (VDF)	46156.14	307.10
Moderately Dense Forests (MDF)	2566.07	17.07
Degraded Forests (DF)	7408.95	49.30
Total	56131.16	373.47

Supplementary Figure S3. Carbon accounting in forest ecosystem (quantity and monetary value in billion INR). Created using the open-source software QGIS 3.10 [<https://www.qgis.org/>] and GRASS GIS 7.8.2 [<https://wgibis.ces.iisc.ac.in/grass/>].



Supplementary Figure S4. Carbon accounting in the mangrove ecosystem (quantity and monetary value in billion INR). Created using the open-source software QGIS 3.10 [<https://www.qgis.org/>] and GRASS GIS 7.8.2 [<https://wgbis.ces.iisc.ac.in/grass/>].



Supplementary Information

Supplementary Table S7. Bio-geo-climate, ecological, environmental, and social variables considered for prioritizing regions (at grid level) based on eco-sensitivity with weights (based on the relative significance)

Sl. No	Variables	Weightage/Ranking (based on the significance)					
		0	2	4	6	8	10
LAND							
1	Forest Cover	0	<15%	15-30%	30-45%	45-60%	>60%
2	Interior forest	0	<15%	15-30%	30-45%	45-60%	>60%
ECOLOGY							
3	Biomass (total Carbon)	0	<300	300-600	600-900	900-1200	>1200
4	Shannon's Diversity	0	<1	1-1.5	1.5-2	2-2.5	>2.5
5	No. of species	0	<50	50-100	100-150	150-200	>200
6	Flora	Not Present	–	–	–	Endemic	–
7	Fauna	Not Present	–	–	–	Endemic	–
GEO - CLIMATIC							
8	Elevation (m)	–	–	<250	250–500	500–750	>750
9	Rainfall (mm)	–	<600	600-1200	1200-1800	1800-2400	>2400
10	Agro-Climatic Zone	–	Hot Dry Arid	Arid	Hot Dry Semi-Arid	Hot Dry Sub Humid	Hot Moist Sub-Humid/Sahyadris
11	Lithology	–	–	Charnokites or Kalaadgi	Peninsular Gneiss	Dharwars or Granite	Deccan Trap
12	Soil	–	coarse loamy	sandy or sandy skeletal	Fragmental or Rocky outcrops	Clayey loamy or Clayey Skeletal	Loamy or Clayey
HYDROLOGY							
13	Stream density	<0.5	0.5-1	1-1.5	1.5-2	2-2.5	>2.5
14	Stream flow	-	<3 months	3 months	4 months	5 months	>6 months
15	Reservoir	not present	–	–	–	Present	-
ENERGY							
16	Solar energy (kWh)	–	-	-	-	<6	>6
17	Wind energy (m/sec)	–	<1.5	1.5-2	2-3.5	3.5-4	>4
18	Bioenergy (Mkcal)	–	<100	100-200	200-400	400-600	>600
SOCIAL							
19	Population Density (persons per sq. km)	–	>1000	1000-500	500-250	250-100	<100
20	Livestock Density (animals/ha)	–	<0.75	0.75-1.5	1.5-2.25	2.25-3	>3
21	Forest dwellers	not present	–	–	–	–	S.T. population

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