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Implementing Reinforcement Learning via Markov Decision Process (MDP) for Wind Shelter Modelling: A Precursor to the Dynamic Line Rating (DLR) Technology Trial in Queensland's Transmission Network

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Outline of Presentation

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- Methodology
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    - Wind
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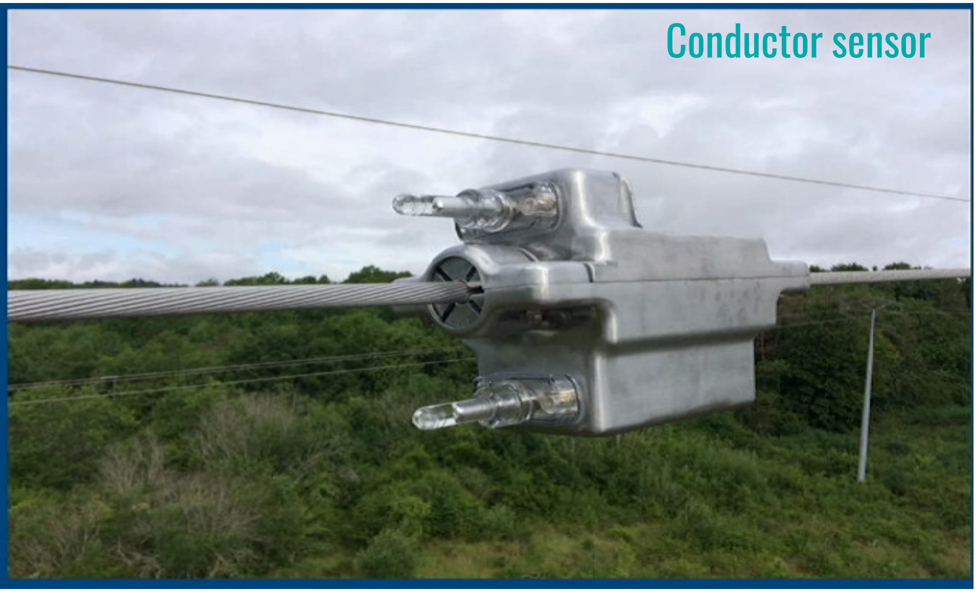
Introduction

Powerlink QLD

- **Queensland Government owned corporation** – one of Australia's leading transmission network companies.
- We own, develop, operate and maintain the **high voltage transmission** network.
- We provide electricity to more than **five million Queenslanders** and **250,000 businesses**.
- Our network runs **1,700km** from north of Cairns to the New South Wales border.
- Comprises **16,500** circuit kilometres of transmission lines and **196** substations

Introduction

- Develop network-wide spatial modelling tool that will assist in identifying critical spans
- Real-Time Ratings Technology Trial Project
  - to identify critical locations of sensor technology and weather stations along transmission lines and corridors



Methodology

- Data Requirements

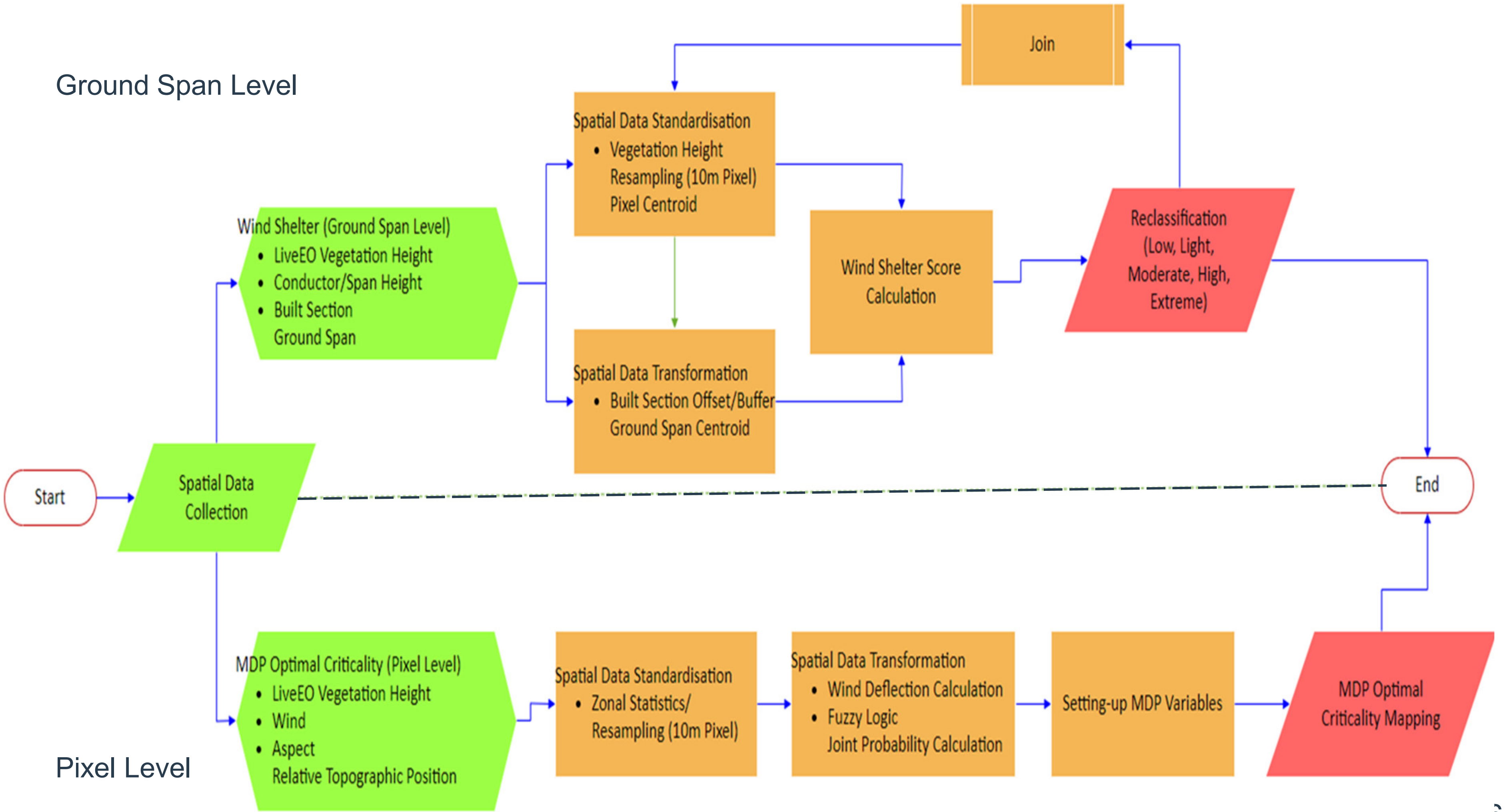
Table 1. Spatial data availability, resolution, and respective sources

Data/Factors	Associated Data	Source	Temporal Statistics	Spatial Resolution
PQ Infrastructure Data	Built Section, Span Height, Ground Span	PQ Enterprise Spatial Database		NA
Vegetation	Foliage Projective Cover	TERN QLD-Long Paddock	Annual (2021)	10m
	Vegetation Height	PQ/Live-EO	Annual (2023)	NA
Relative Topographic Position	Topographic Position	Geoscience Australia	(2018)	~90m
Elevation	DEM	Geoscience Australia	(2000)	1 Second Grid (~30m)
	Slope	Generated		1 Second Grid (~30m)
	Aspect	Generated		1 Second Grid (~30m)
Wind	Eastward Wind Speed	ECMWF*	36 years of monthly ERA5 (1985-2020)	0.25° x 0.25°
	Northward Wind Speed	ECMWF*	36 years of monthly ERA5 (1985-2020)	0.25° x 0.25°
	Wind Direction	Calculated		

*Bureau of Meteorology (BoM) has partnered with the European Centre for Medium-Range Weather Forecasts (ECMWF) to collaborate and share data, knowledge sharing and capabilities exchange (Source: Australian Bureau of Meteorology partners with ECMWF | Meteorological Technology International).

Methodology

- Overall Analytical Framework

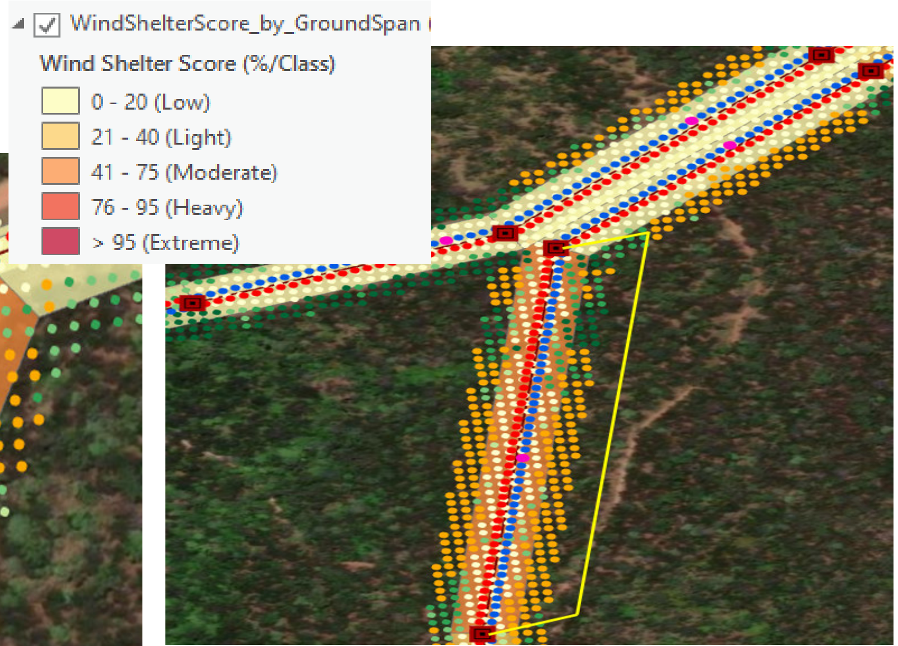


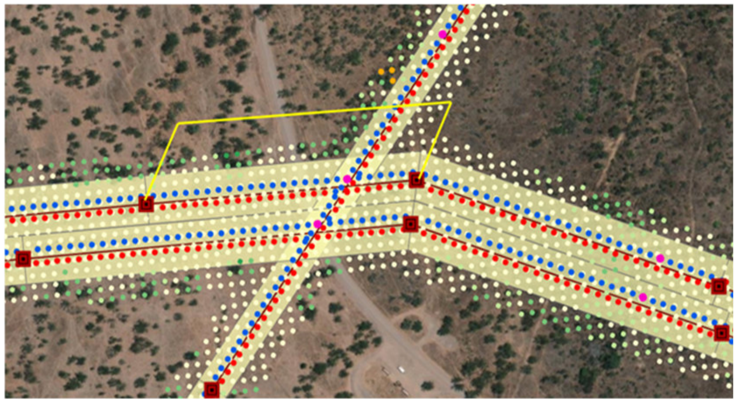
Ground Span Level

- Wind Shelter Scoring and Classification by Ground Span

Ground Span Level

- Wind Shelter Scoring and Classification





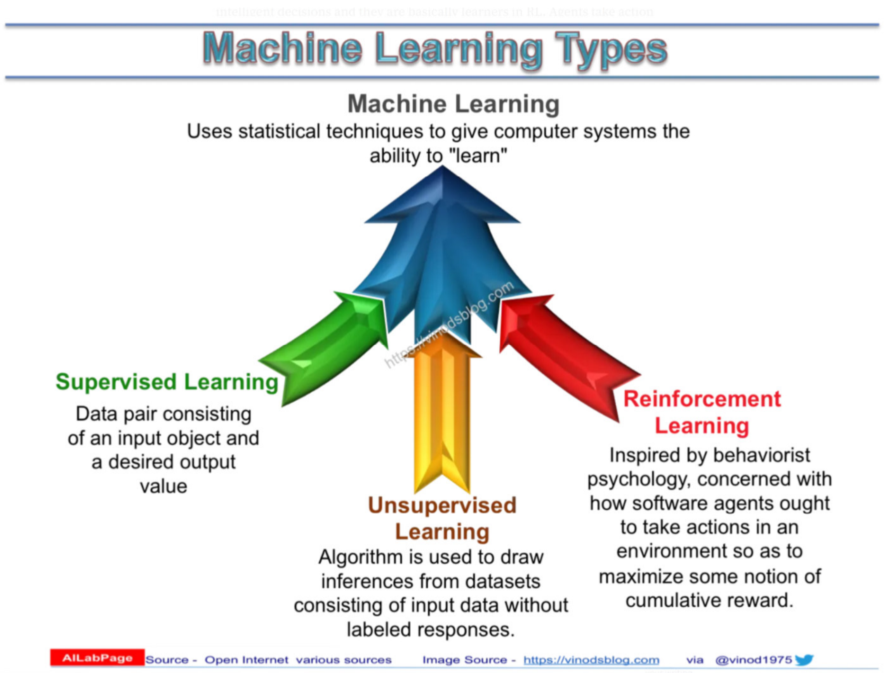
Project is after heavy to extremely wind-sheltered ground spans

What’s going on within & around Ground Span?

- Ground span is a scene-level analysis
  - aimed at labelling each patch/ground span polygon with a semantic class based on its content (i.e. scoring & degree of sheltering)

- Can we further label each pixel with a class to refine our action/decision and find optimal policy?

- Implement Reinforcement Learning (RL) using Markov Decision Process (MDP)
  - stochastic dynamic programming to model sequential decision-making
  - applied in robotics, engineering, energy regulation, hydropower-reservoir operations, risk management, land-use planning, etc.



Source: per link above

Pixel Level (Solving Optimisation Problem)

- Finding Optimal Policy using Markov Decision Process (MDP)

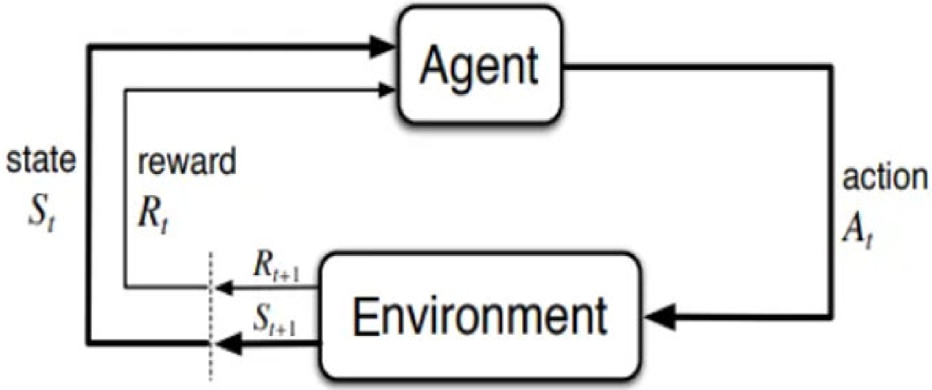


Figure 2. The agent-environment interaction characterizing the Markov Decision Processes (MDP)

Source: Sutton and Barto (2017). Reinforcement Learning: An Introduction

- MDP Variables (SATR)
  - a finite set of states **s** ∈ **S**.
  - a finite set of actions ***a*** ∈ ***A***
  - a transition function ***T* (*s'*|*s*,*a*)** returning the probability of reaching state ***s'***, given the current state ***s***, the current action ***a***
  - a reward function ***R* (*s*,*a*,*s'*)** returning a scalar reward based on reaching the new/next state ***s'***, after being in state ***s***, and taking action ***a***.

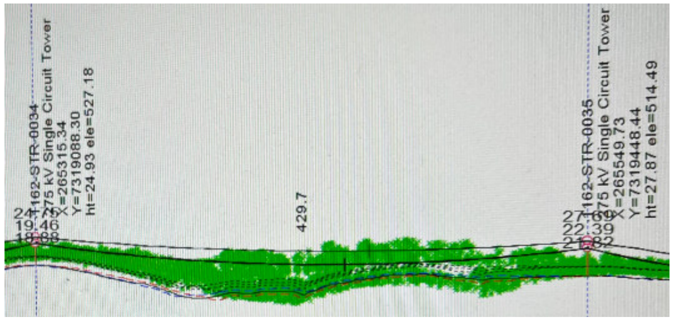
Pixel Level

Defining the MDP Variables

Wind Shelter Score

- Current and New State Variables
  - Wind shelter scores and classification as the ***current State/Condition (s)***
  - Scoring was generally guided (not all) by EPRI's technical documentation
  - Classification from Debashis

Wind Shelter Score (%)	Classification
0 – 25	Low
26 – 40	Light
41 – 75	Moderate
76 – 95	Heavy
> 95	Extreme



Source/Acknowledgment: Debashis Paul

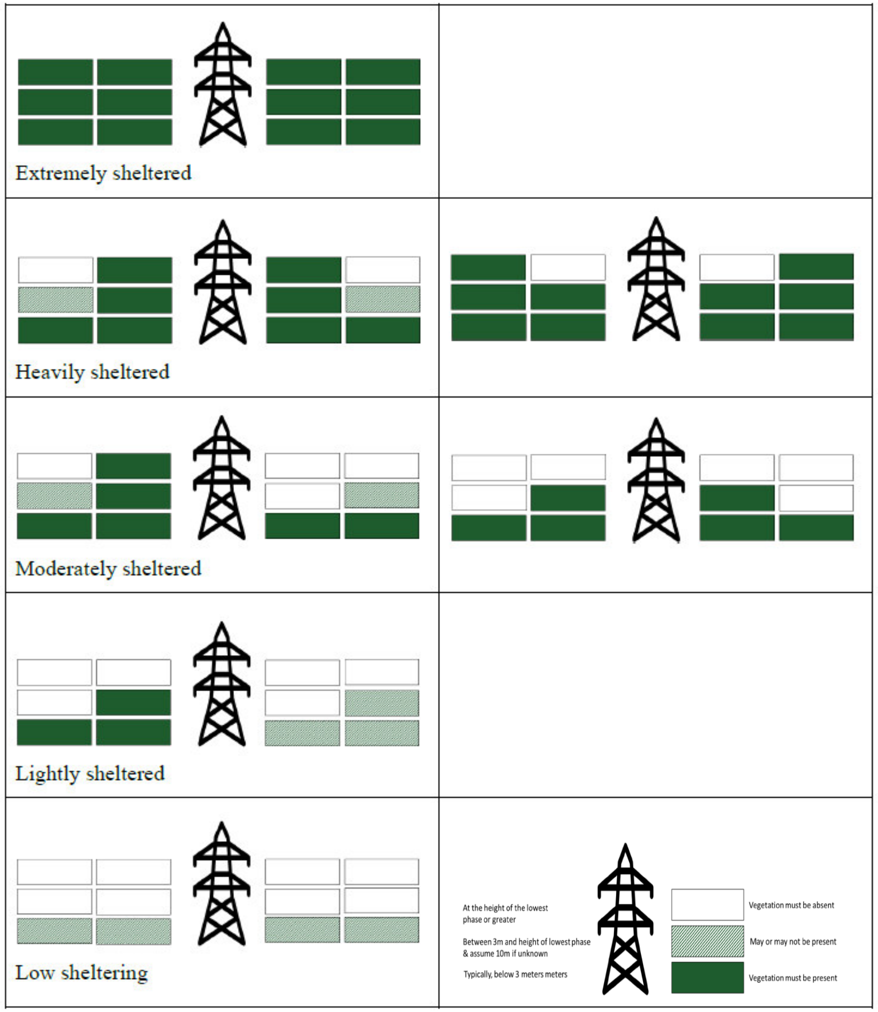


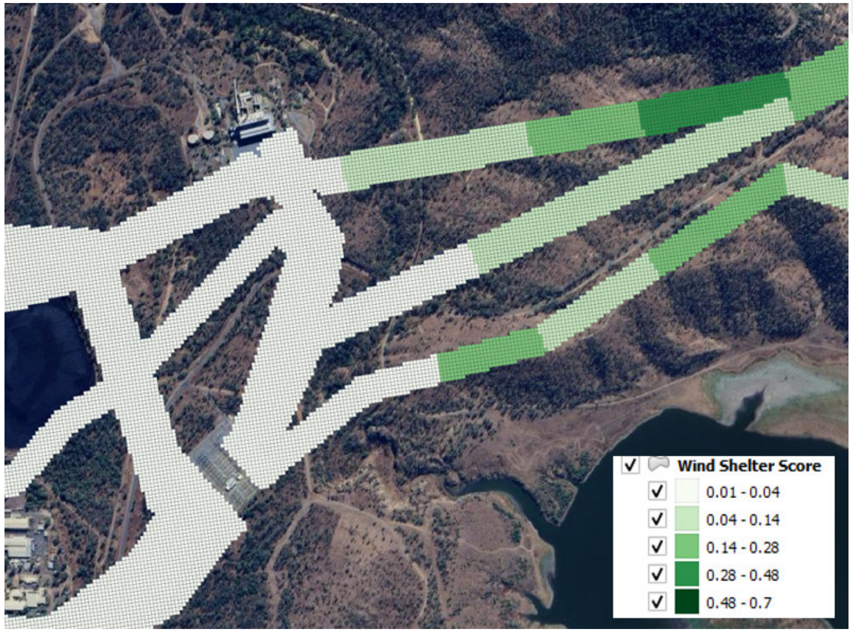
Figure 3. Obstruction based on vegetation height and radial distance (Adopted from EPRI Technical Update, 2023)

Pixel Level

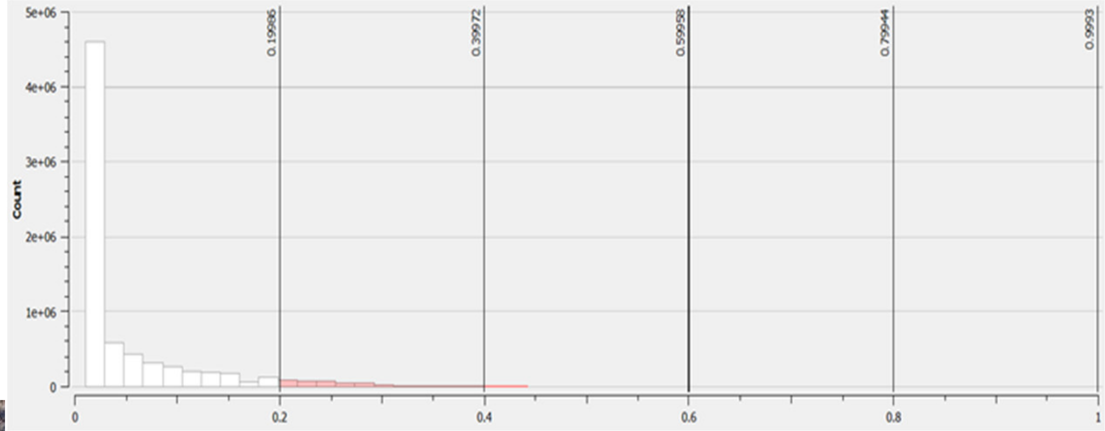
Defining the MDP Variables

Wind Shelter Score

- Current State Variable (*s*)
  - 5 current states/conditions
    - Low
    - Light
    - Moderate
    - High
    - Extreme



Wind shelter score histogram



Low Sheltering — Extreme Sheltering

Low Preference — High Preference

- Real-time rating sensor requires heavily sheltered or vegetated areas

Pixel Level

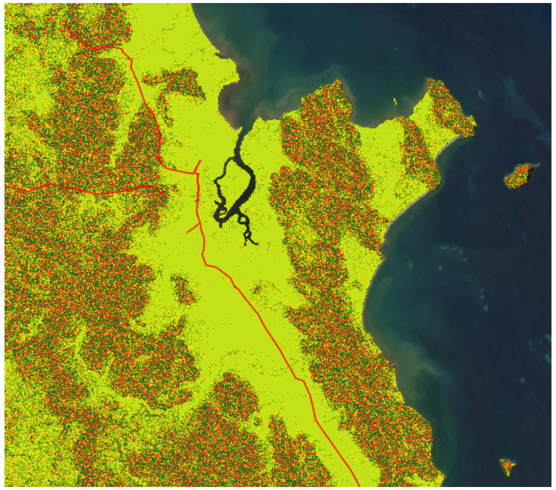
Defining the MDP Variables

WAR Variables

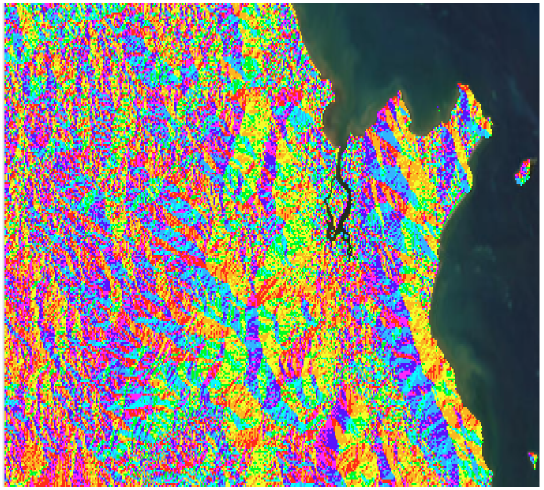
- New State Variable (*s'*)
  - 5 new states/conditions
    - Low
    - Light
    - Moderate
    - High
    - Extreme

Real-time rating sensor requires:

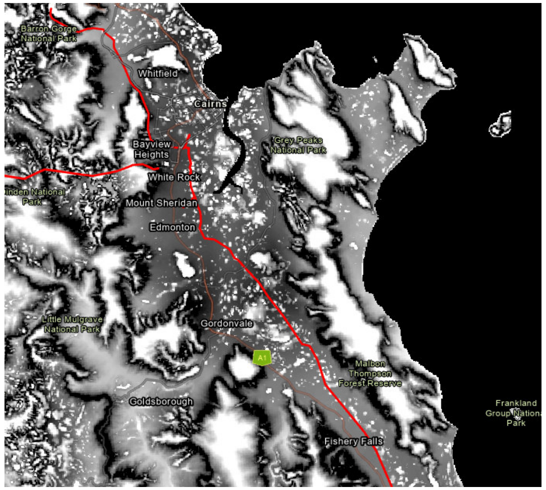
- Uneven topography
- Steep slopes & rough terrains (i.e. leeward/windward sides) – winds must deflect/flow freely.
- South-facing slopes with low influx of solar energy



Wind Deflection (W)



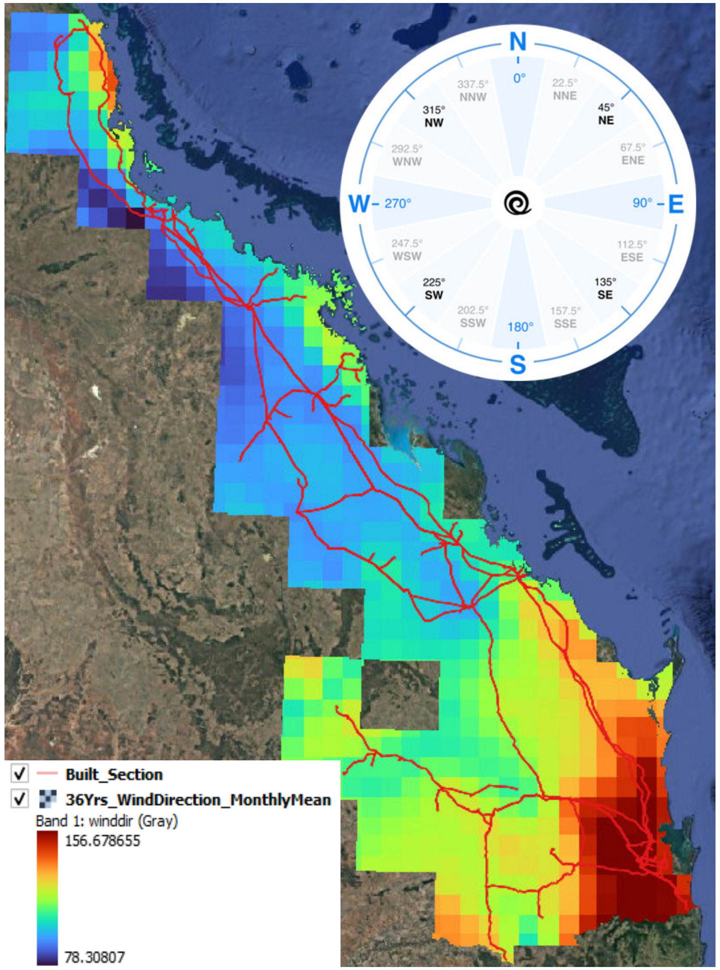
Aspect (A)



Relative Topographic Position (R)

Pixel Level

Wind Variable



Defining the MDP Variables

- BoM – ECMWF partnership
- ERA5 - 36 years

Date Coverage (1985-2020)

ECMWF ERA5 Monthly

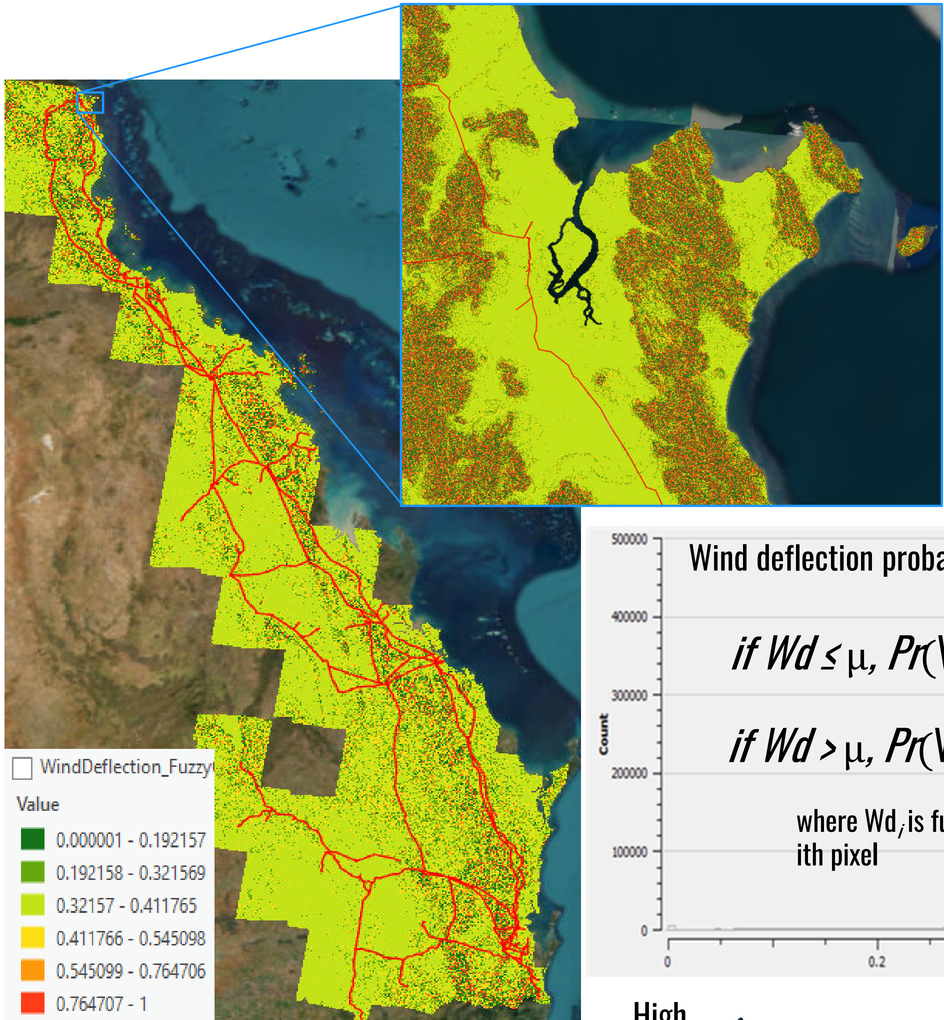
Area of Interest

Calculate Wind Direction
- *u10* component (m/s – 10m)
- *v10* component (m/s – 10m)

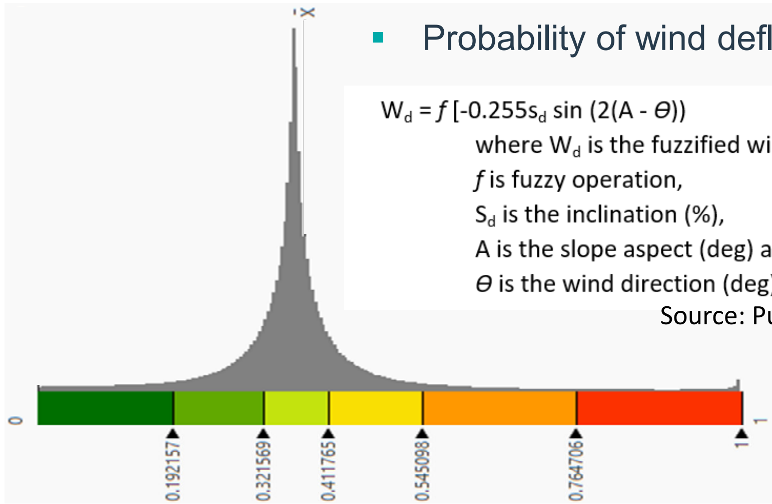
Get the Monthly Mean

Pixel Level Defining the MDP Variables

Wind Variable



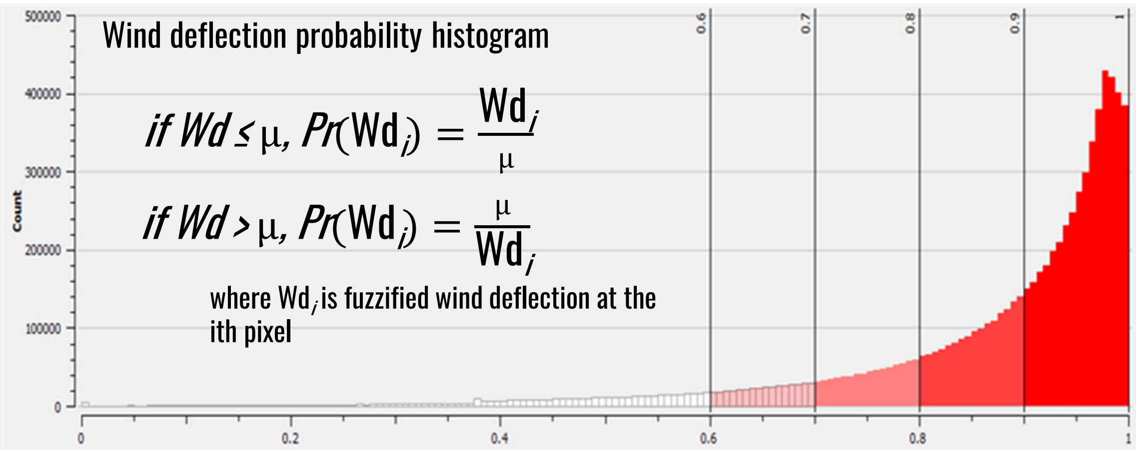
- Fuzzy Gaussian of wind deflection
- Probability of wind deflection



$W_d = f\,[-0.255 s_d \sin(2(A - \Theta))$

where W_d is the fuzzified wind deflection value,
f is fuzzy operation,
S_d is the inclination (%),
A is the slope aspect (deg) and
Θ is the wind direction (deg)]

Source: Purves *et al.* 1998



Wind deflection probability histogram

$$if\ Wd \leq \mu,\ Pr(Wd_i) = \frac{Wd_i}{\mu}$$

$$if\ Wd > \mu,\ Pr(Wd_i) = \frac{\mu}{Wd_i}$$

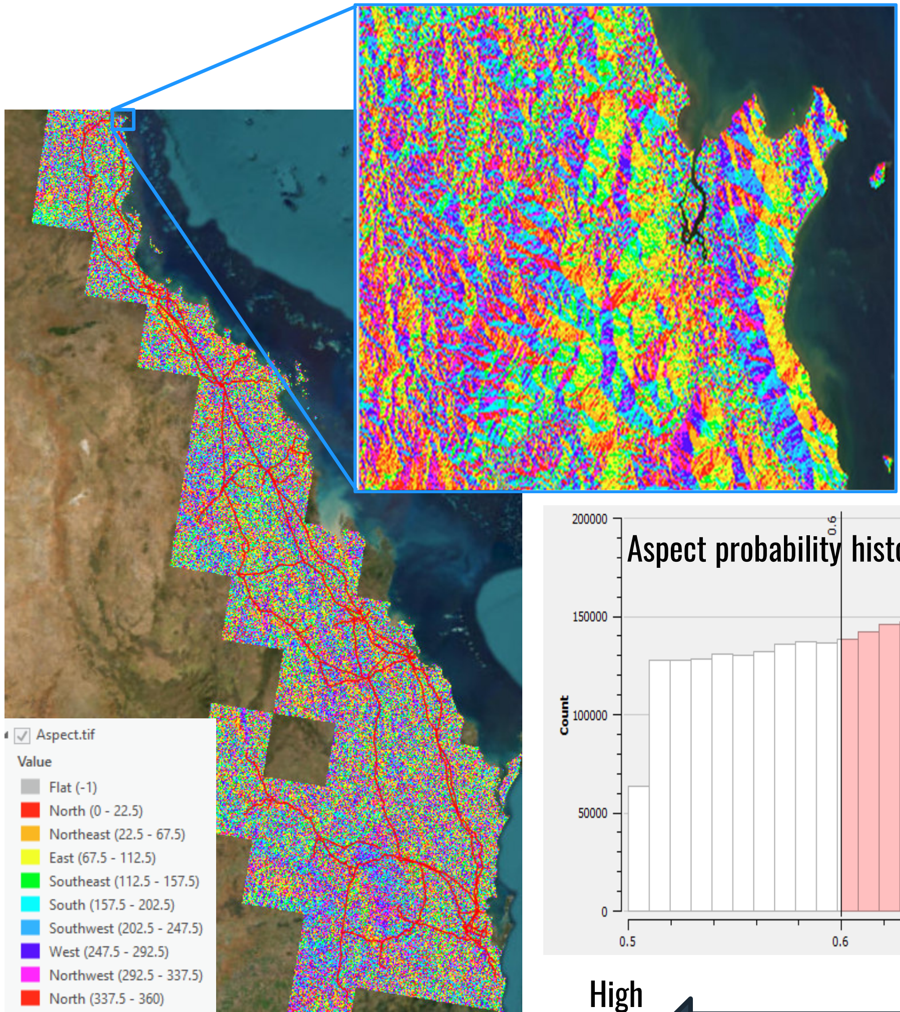
where Wd_i is fuzzified wind deflection at the ith pixel

High Preference ← Low Preference

Pixel Level

Defining the MDP Variables

Aspect Variable

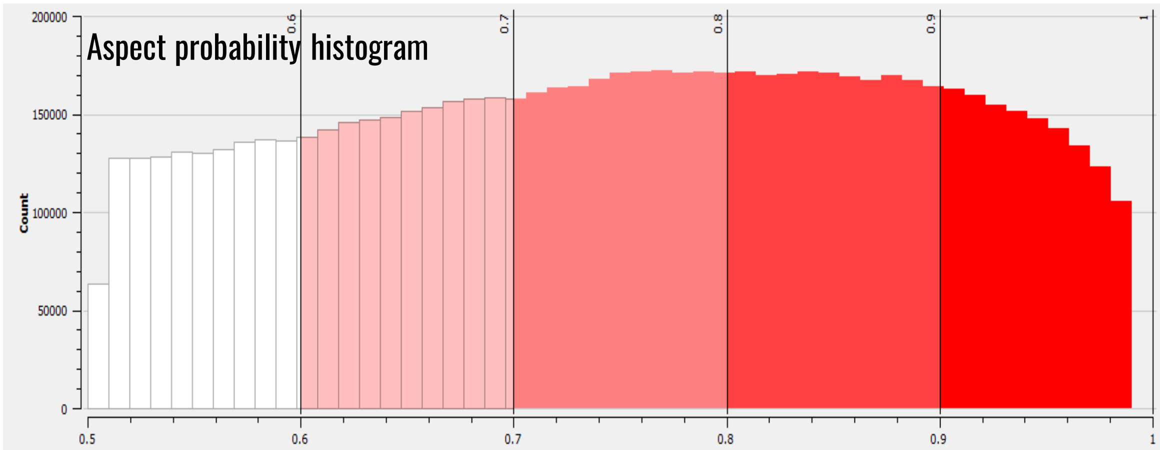


- Aspect probability

$$\textit{if Aspect} < 180,\ Pr(\mathrm{A}_i) = 1 - \frac{\mathrm{A}_i}{360}$$

$$\textit{if Aspect} \geq 180,\ Pr(\mathrm{A}_i) = \frac{\mathrm{A}_i}{360}$$

where A_i is the aspect value at the ith pixel

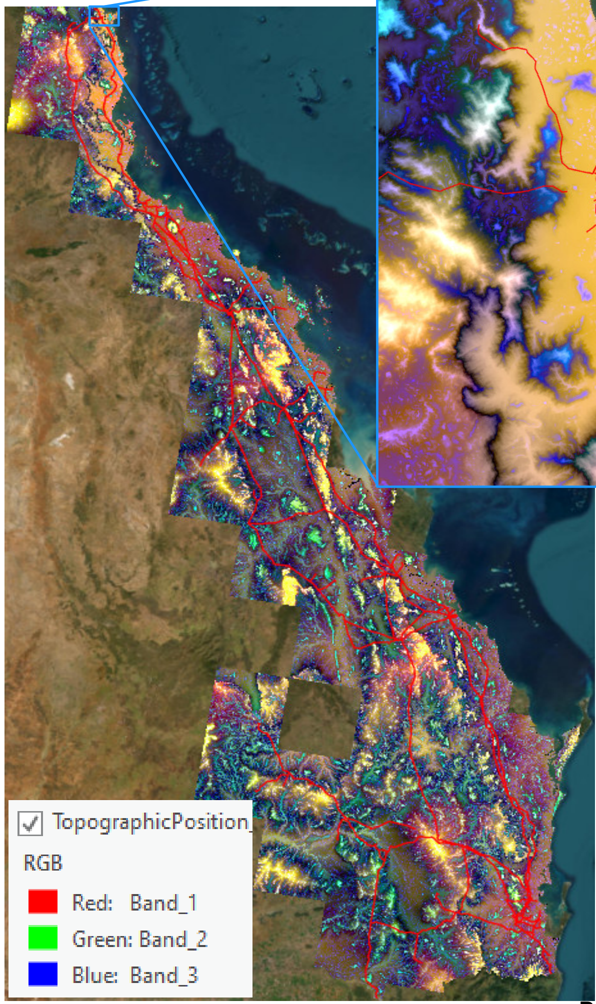


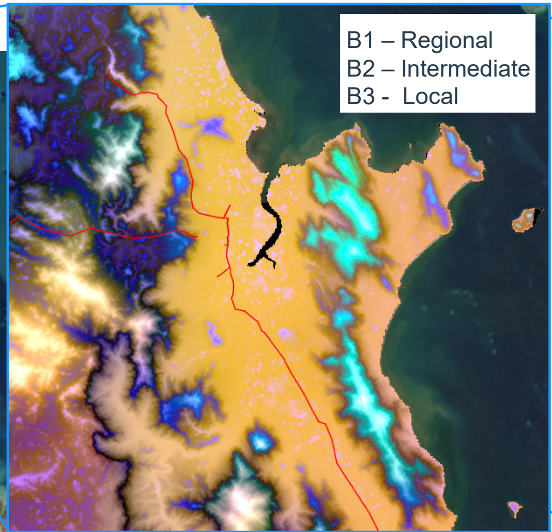
High Preference ← Low Preference

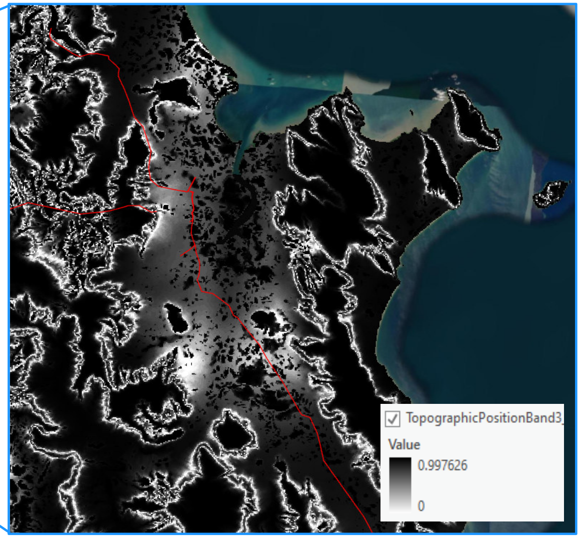
Pixel Level

Defining the MDP Variables

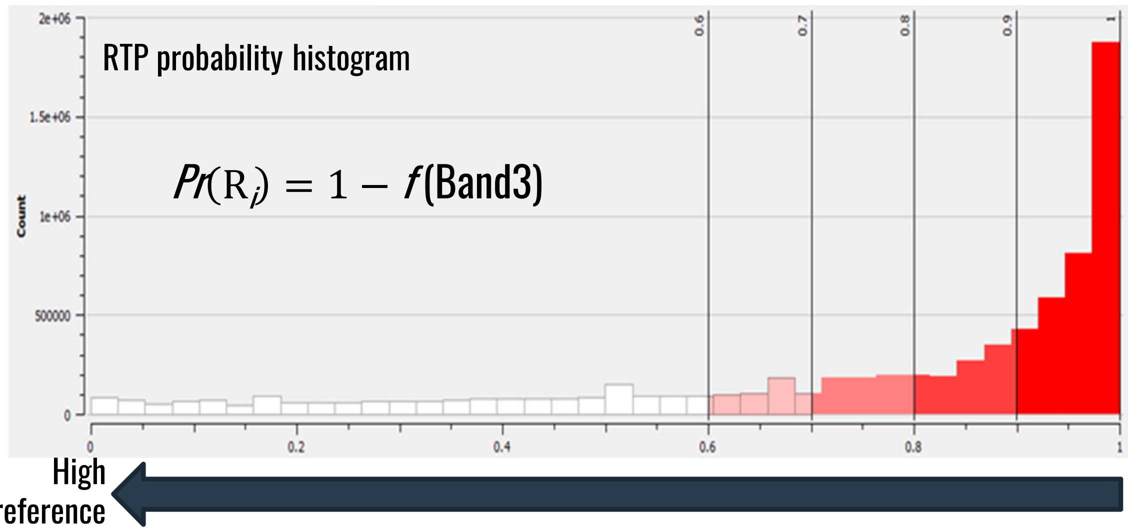
Relative Topographic Position (RTP) Variable







- Local scale position of landforms
- RTP probability



Pixel Level

Defining the MDP Variables

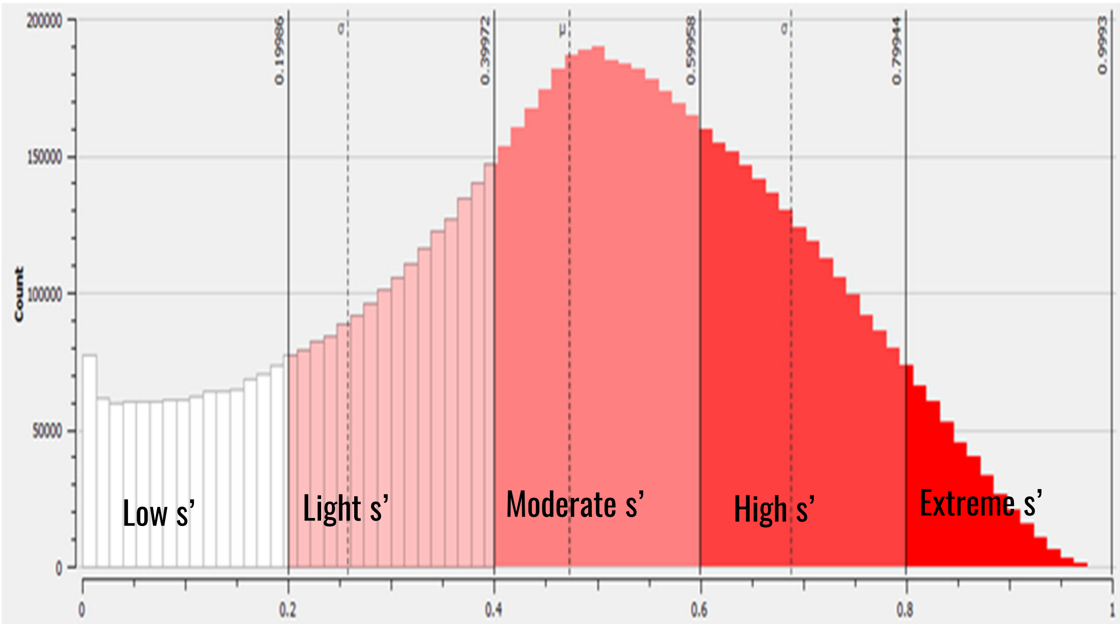
- Transition Probability [T(s,a,s')]

$$T_i(s_{i,}a_{i,}s'_i) = [1 - WS_i] \cap [Pr(WAR_i)]$$

where

WS_i is current state wind shelter score at the ith pixel

$Pr(WAR_i) = Pr(Wd_i) \cap Pr(A_i) \cap Pr(R_i)$ at the ith pixel



Transition probability histogram

What to do with WAR probabilities and preferences?

New State/ Condition (s')	Description
Low	Low WS, Wd, even RTP & north-facing aspect
Light	Light WS, Wd, RTP & NE/NW-facing aspect
Moderate	Moderate WS, Wd, RTP & E/W-facing aspect
High	High WS, WD, RTP & SE/SW-facing aspect
Extreme	Extreme WS, Wd, RTP & south-facing aspect

Pixel Level

Defining the MDP Variables

- Actions (a_i) and Rewards $(R(s_i, a_i, s'_i)$
- Discounting Factor [$\gamma \in [0, 1)$] = 0.9

New State/ Condition (s')	Description	Reward $(R(s_i, a_i, s'_i)$	Actions/ Assigned Criticality (a_i)
Low	Low WS, Wd, even RTP and north-facing aspect	-10	Low-Critical
Light	Light WS, Wd, RTP and NE/NW-facing aspect	-5	Lightly Critical
Moderate	Moderate WS, Wd, RTP and E/W-facing aspect	0	Moderately Critical
High	High WS, WD, RTP and SE/SW-facing aspect	+5	High-Critical
Extreme	Extreme WS, Wd, RTP and south-facing aspect	+10	Extremely Critical

Completed MDP Matrix

- Organised & processed the MDP matrix in R
- Value iteration
- Finding optimal policy/criticality
  - Bellman Equation

Initialize $V(s)$ arbitrarily, for all $s \in \mathcal{S}$
Initialize θ to a small positive value

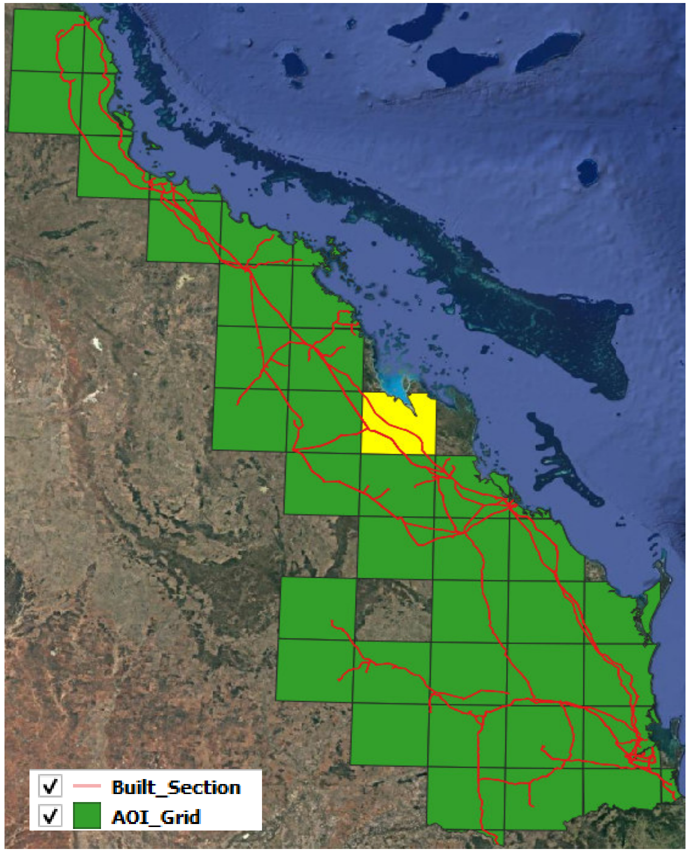
Loop:
$\quad \Delta \leftarrow 0$
$\quad$ Loop for each $s \in \mathcal{S}$: *For every state*
$\quad\quad v \leftarrow V(s)$
$\quad\quad V(s) \leftarrow \max_a \sum_{s',r} p(s', r|s, a)[r + \gamma V(s')]$ *For every available action* *For every resulting next state after taking a in s*
$\quad\quad \Delta \leftarrow \max(\Delta, |v - V(s)|)$
Until $\Delta < \theta$

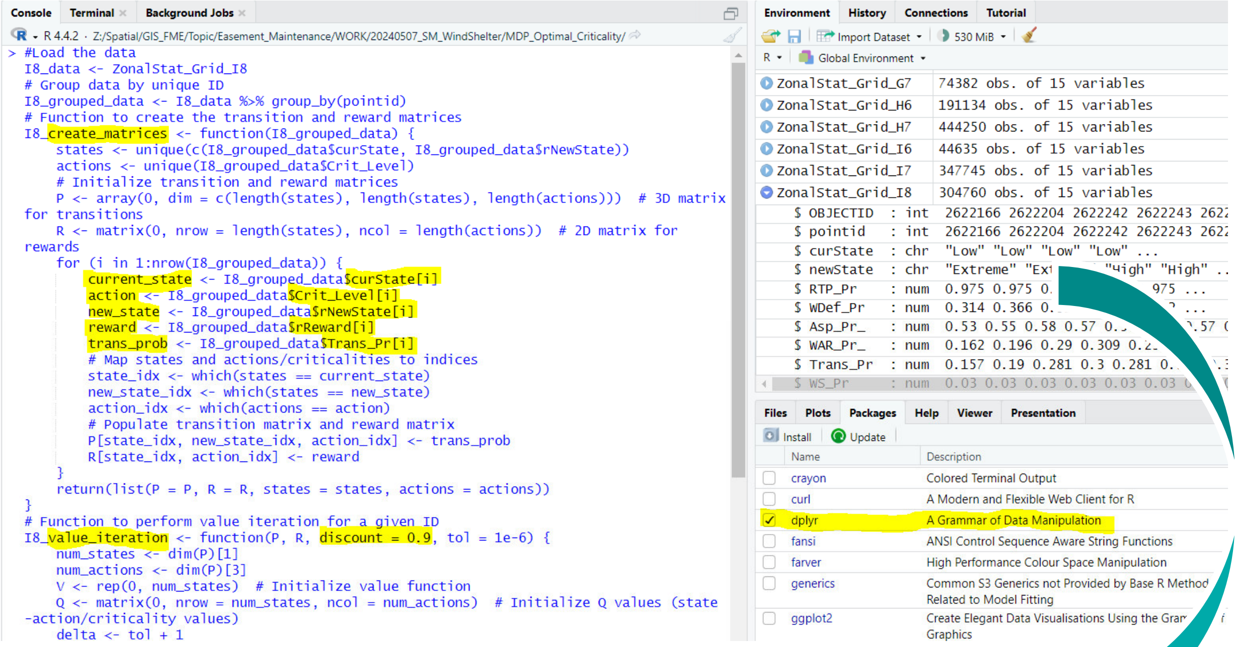
Output a deterministic policy, $\pi \approx \pi*$, such that
$\pi(s) \leftarrow \text{argmax}_a \sum_{s',r} p(s', r|s, a)[r + \gamma V(s')]$

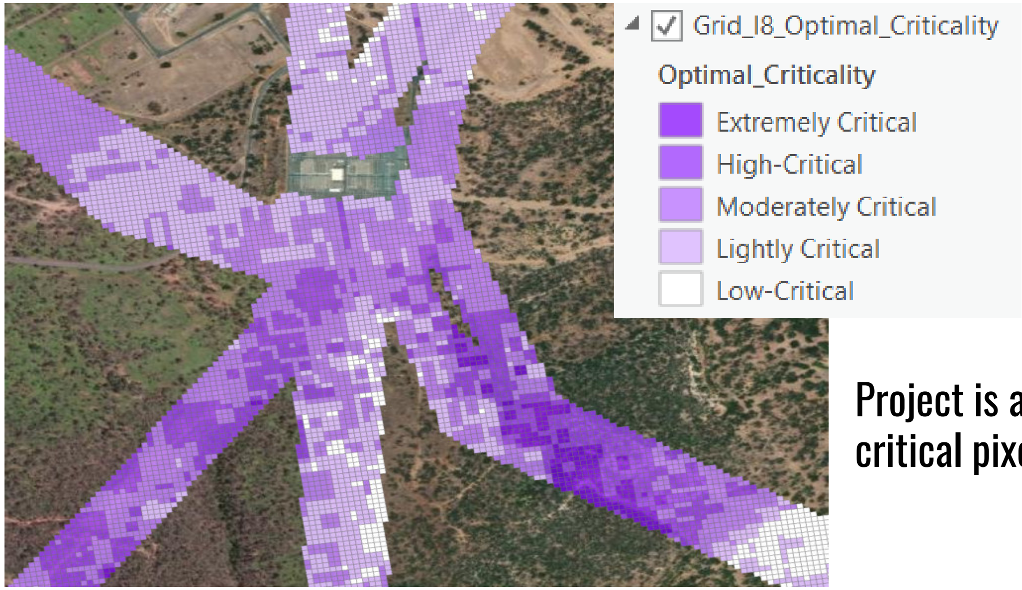
Source: Bettosi (2023)

Pixel Level

- Solving MDP Optimal Criticality
  - 41 MDP grids







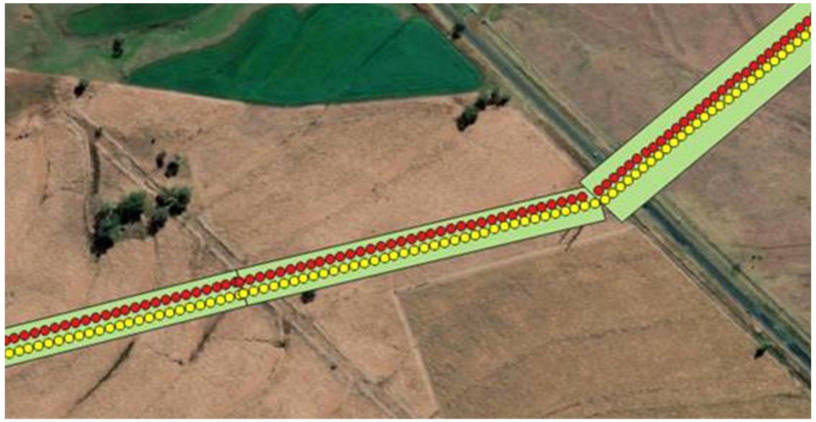
Project is after extremely critical pixels (areas)

- [Wind Shelter Web Map]

Accuracy Assessment

- Ground Span Level
  - missed 180 out of 27,001 spans (99.33% capture ratio)
  - manual corrections

Before manual correction



After manual correction

- Pixel Level
  - 1:1 match/correspondence between pre-defined actions and the resulting optimal criticalities
  - Subject to interpretation and decision appetite

Challenges & Limitations

- Complex process and computationally intensive
- Up-to-date availability of spatial data
- Use of variable spatial data resolution
  - Data were resampled to 10m pixel size
- LiveEO's vegetation height
  - maximum value of the data range was used as the height of pixel centroid
- MDP action-reward pairing and optimal criticality are subject to interpretation.

Takeaways

- Integral part of project policy and decision-making (where, how many sensors, how much $$$)
- Strengthened collaboration between Spatial and Transmission Line Strategies

Thank you!