Old-growth forests detection using multimodal deep learning from remote sensing data

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What is an old growth forest?

Old-growth forest = maturity + ancientness

The **ancientness** *of a forest refers to the time elapsed since the forest was established, independently of past and current management.* (Cateau et al., 2015)

The **maturity** *refers to the stage of natural development of a forest stand.* (Cateau et al., 2015)

Why studying old growth forest?

Old-growth forests: an essential ecological role

- Carbon storage and sequestration (Luyssaert et al., 2008)
- Climate regulation (Watson et al., 2018)
- Refuges for rare and specialized biodiversity (Paillet et al., 2010)

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Very scarce in France and Europe (Massin, 2024) :

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The EU aims to protect old-growth forests by 2030 (Sabatini et Al., 2021)
$\rightarrow$ The first step is to detect them, at large scale across the territory

Field inventories: precise but costly

Field assessment: ecological indicators (Cateau et al., 2015)

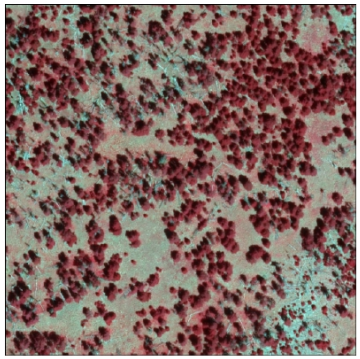
- deadwood (standing or fallen)
- microhabitats
- senescent trees
- living trees with very large diameters

Limitations : time-consuming method, difficult to scale up

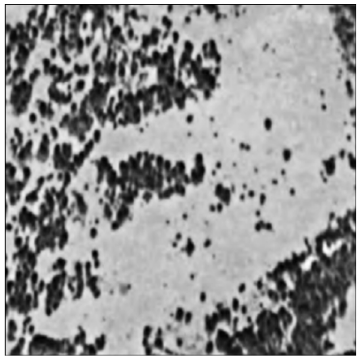
An approach: using remote sensing

- Old-growth forests exhibit a **distinctive structural complexity**, visible from above
- **Hypothesis:** A deep learning model can learn to recognise old-growth forest patterns from multi-source remote sensing data
- **Objective:** Develop a data fusion model to detect and map old-growth forests from remote sensing data

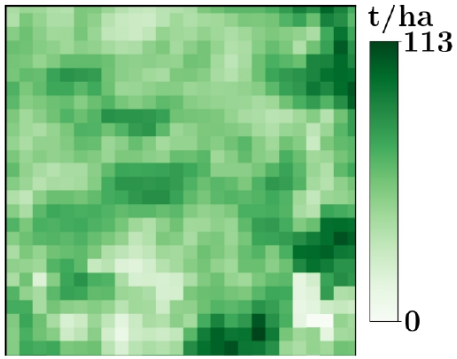
Input data: four complementary modalities



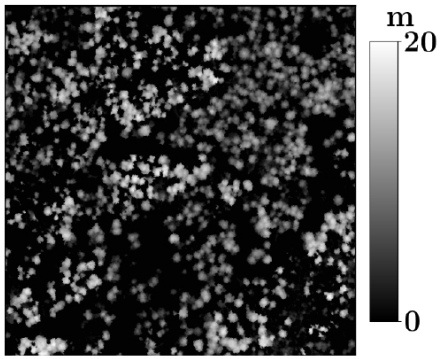
Colour-Infra**R**ed : CIR



Historical imagery : Hist



Biomass : Biom

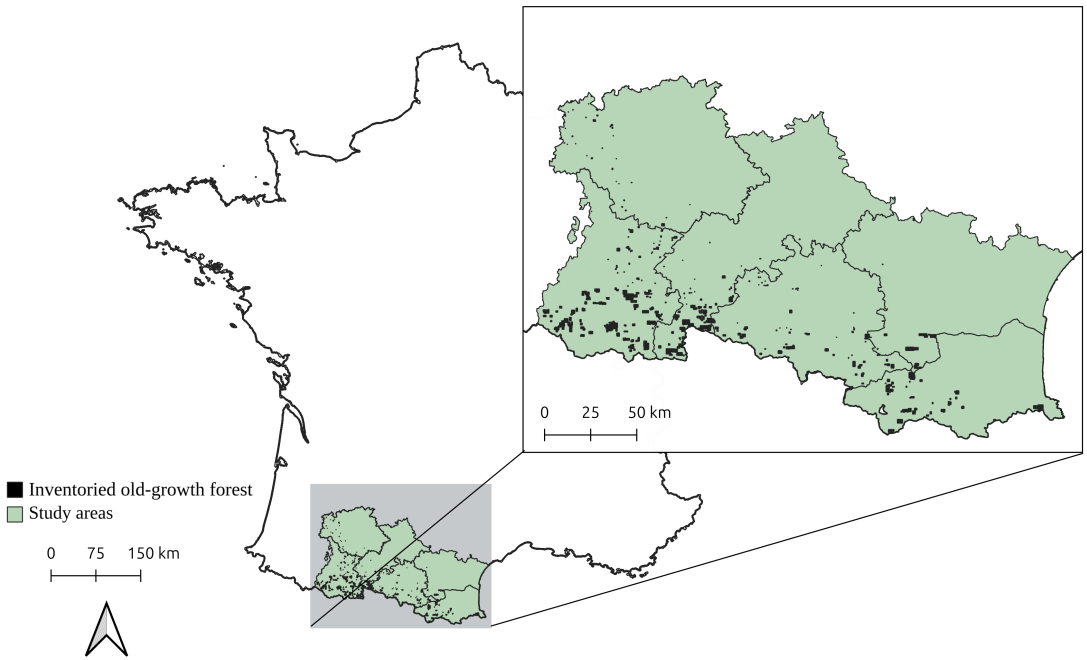


Canopy **H**eight **M**odels : CHM

Data description

Ground truth

- Old-growth forest map of Occitanie (Gouix & Savoie, 2019)

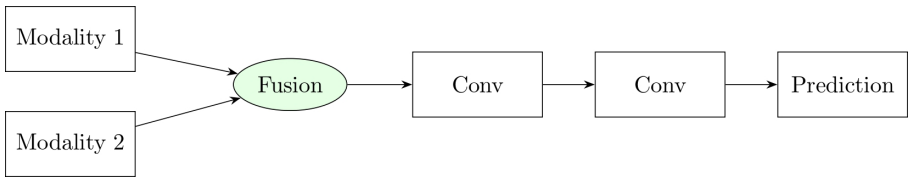


Training data

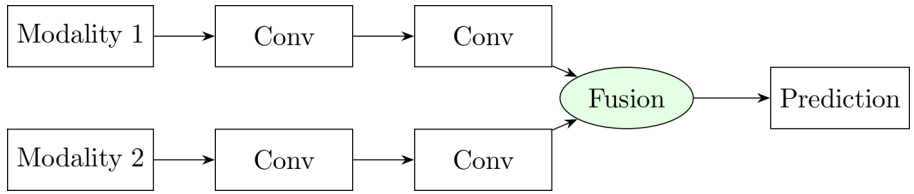
- Total study area: 35 300 ha
- 7 300 patches of 512×512, 50 cm resolution
- Class distribution: non-forest 15%, forest 60%, old-growth 25%
- Split: 70% train, 20% val, 10% test

Modality fusion

We compare two different ways to fuse data (Hong et al., 2020).



Early Fusion



Late Fusion

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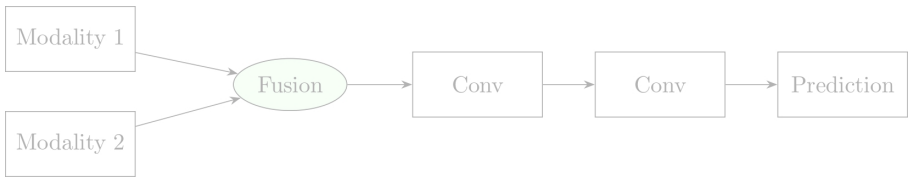

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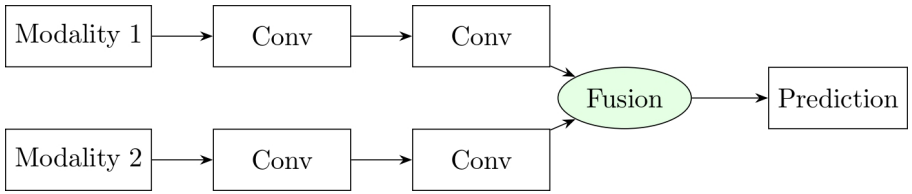
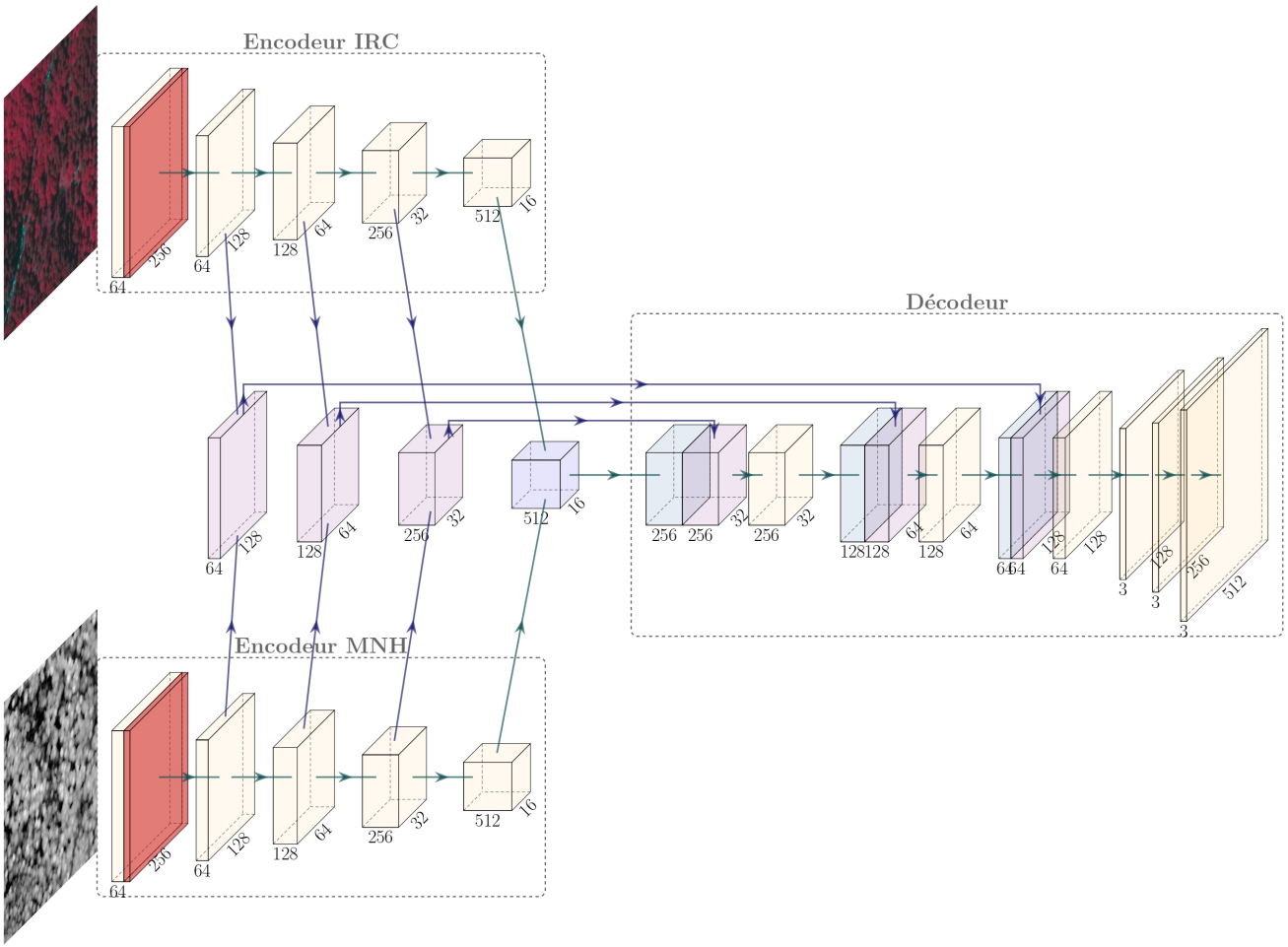


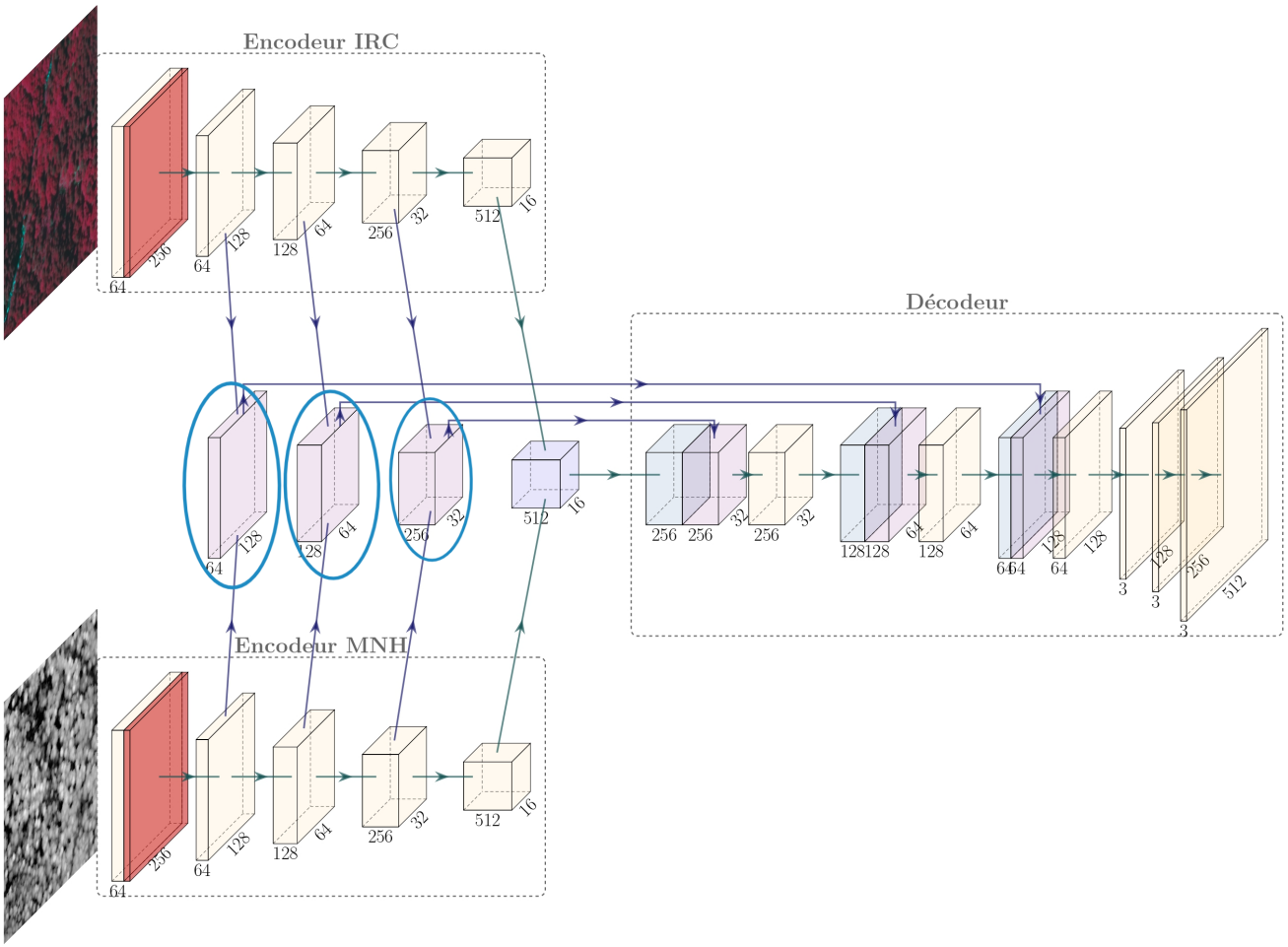
Late Fusion

Model architecture : Late fusion



The fusion module is adapted from MIPANet (Zhang & Xie, 2024).

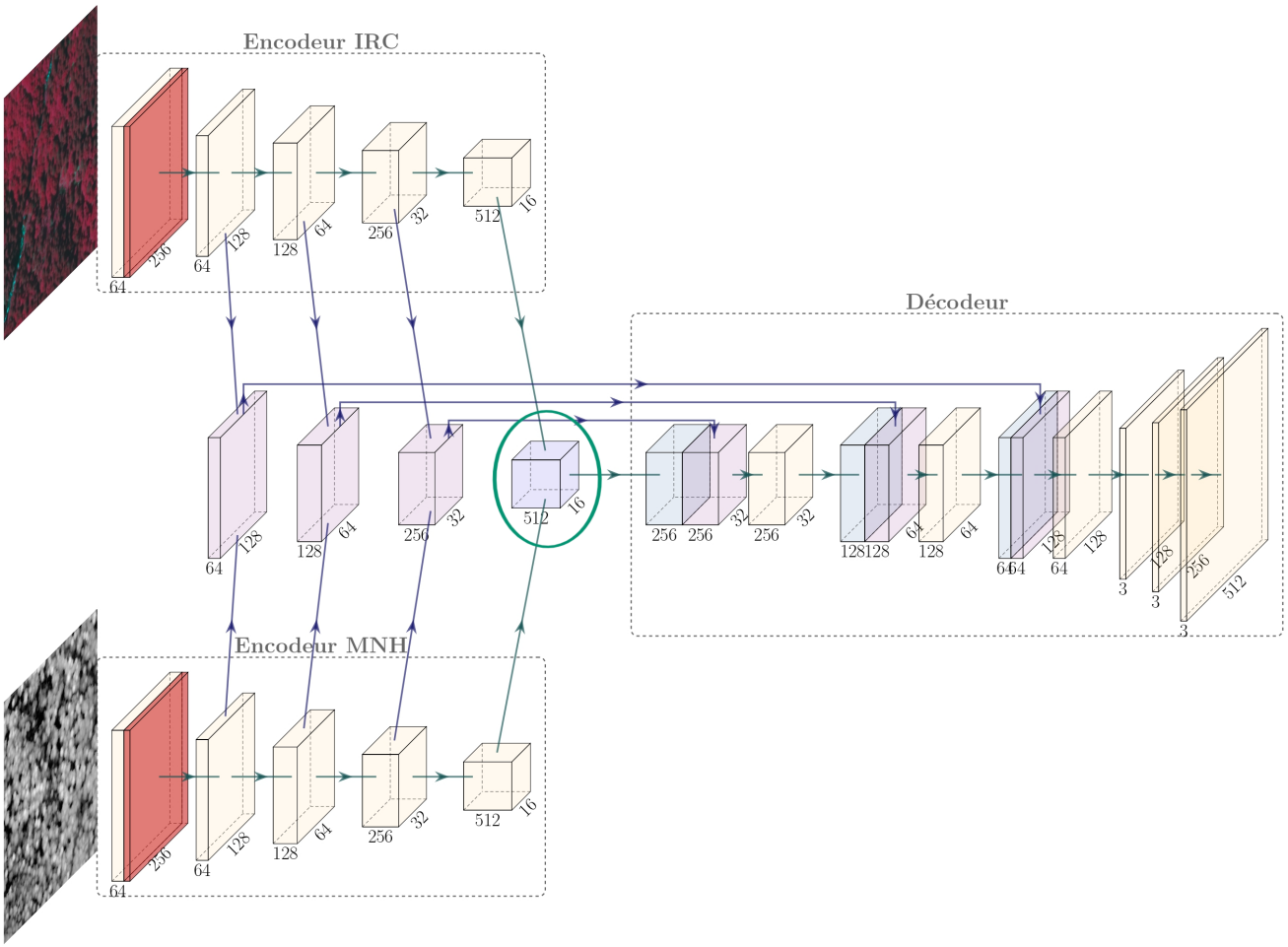
Model architecture : Late fusion



Fusion module for the skip connections $\rightarrow$ weights each channel by its importance

The fusion module is adapted from MIPANet (Zhang & Xie, 2024).

Model architecture : Late fusion



Fusion module for the last representations → multi-head cross-attention

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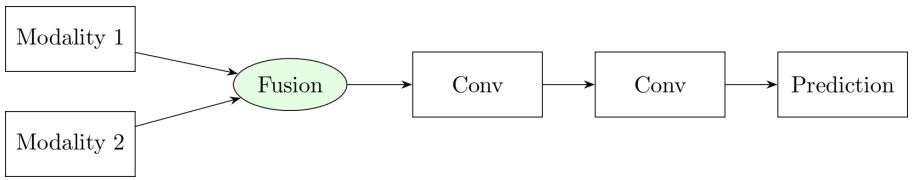

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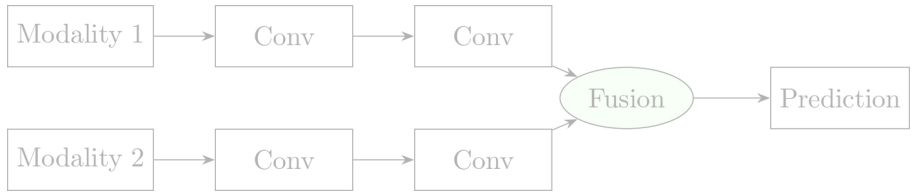

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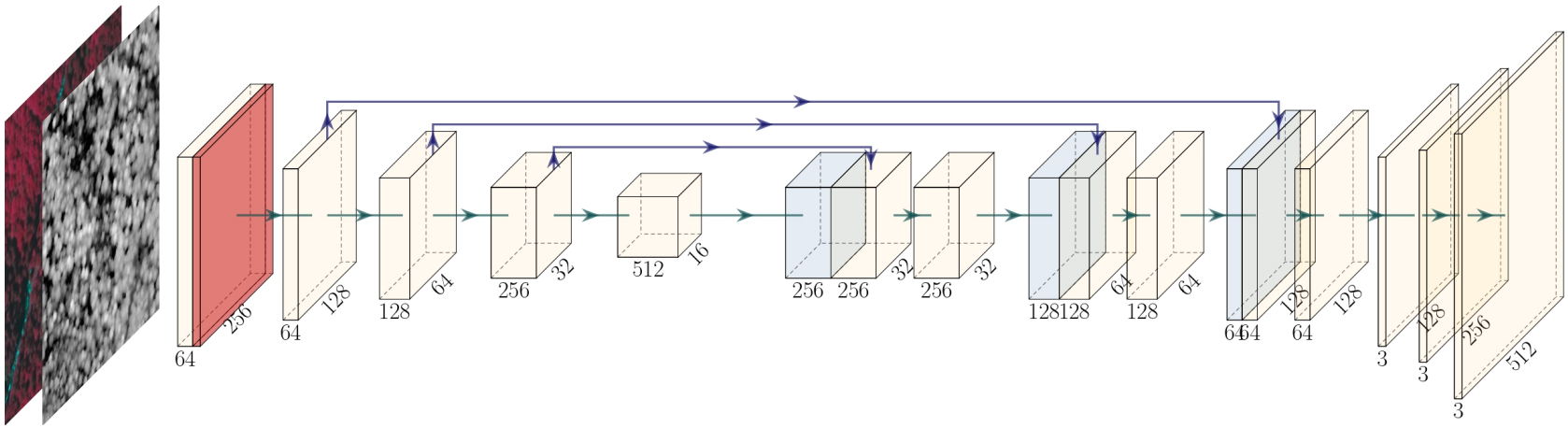

ResNet18 encoder, MobileNetV2 decoder

Results: three questions

Q1 Which modality is most effective for detecting old-growth forests?

Q2 Does multimodality improve detection?

Q3 Does late fusion bring an added value?

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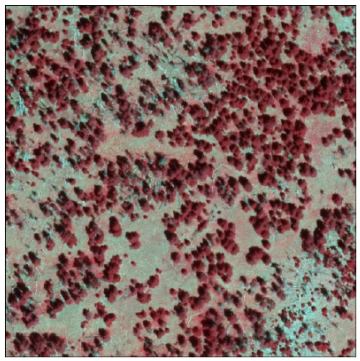
Evaluation metrics

We evaluate with the IoU of the old-growth forest class, and the overall accuracy (OA).

Results

Strategie	Modalities	IoU_{ogf}	OA
Modalité unique	IRC	46.6	78.3
Early fusion	IRC + MNH	48.3	79.1
	IRC + Biom + MNH + Histo	49.3	80.3
Late fusion	IRC + MNH	52.7	81.9
	CIR + Biom + CHM + Histo	**53.7**	**82.4**



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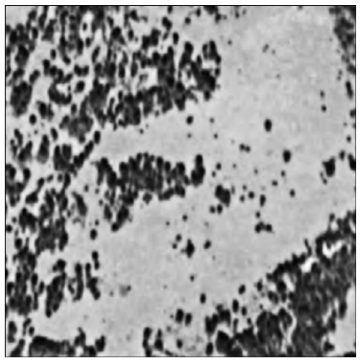

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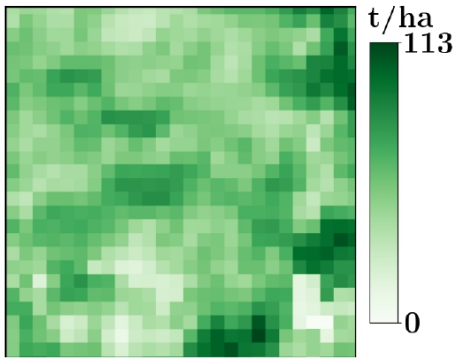

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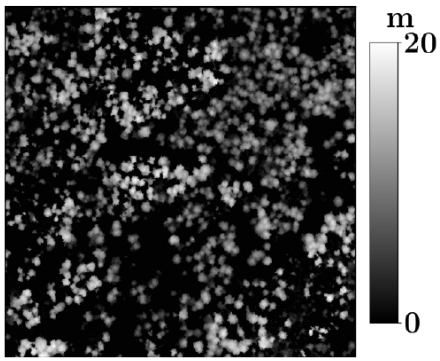
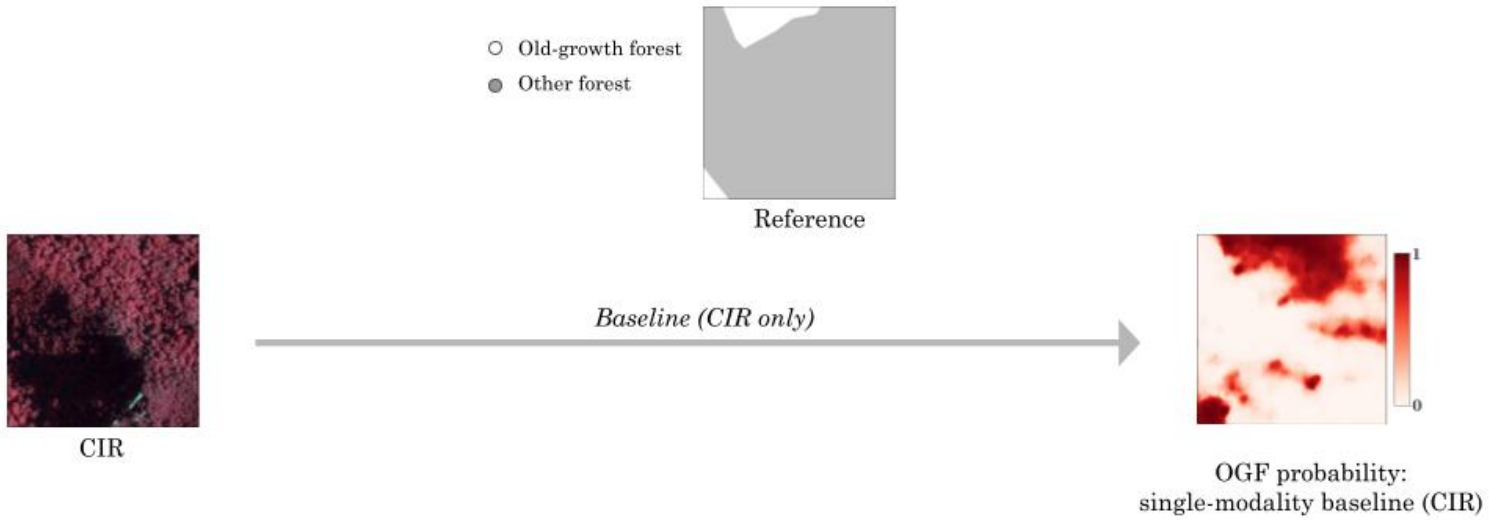


Canopy **H**eight **M**odels : CHM

Prediction examples: limits of CIR, recovered by LiDAR



- Limit of IRC (passive sensor):
  shadows in mountain hollows → loss of signal

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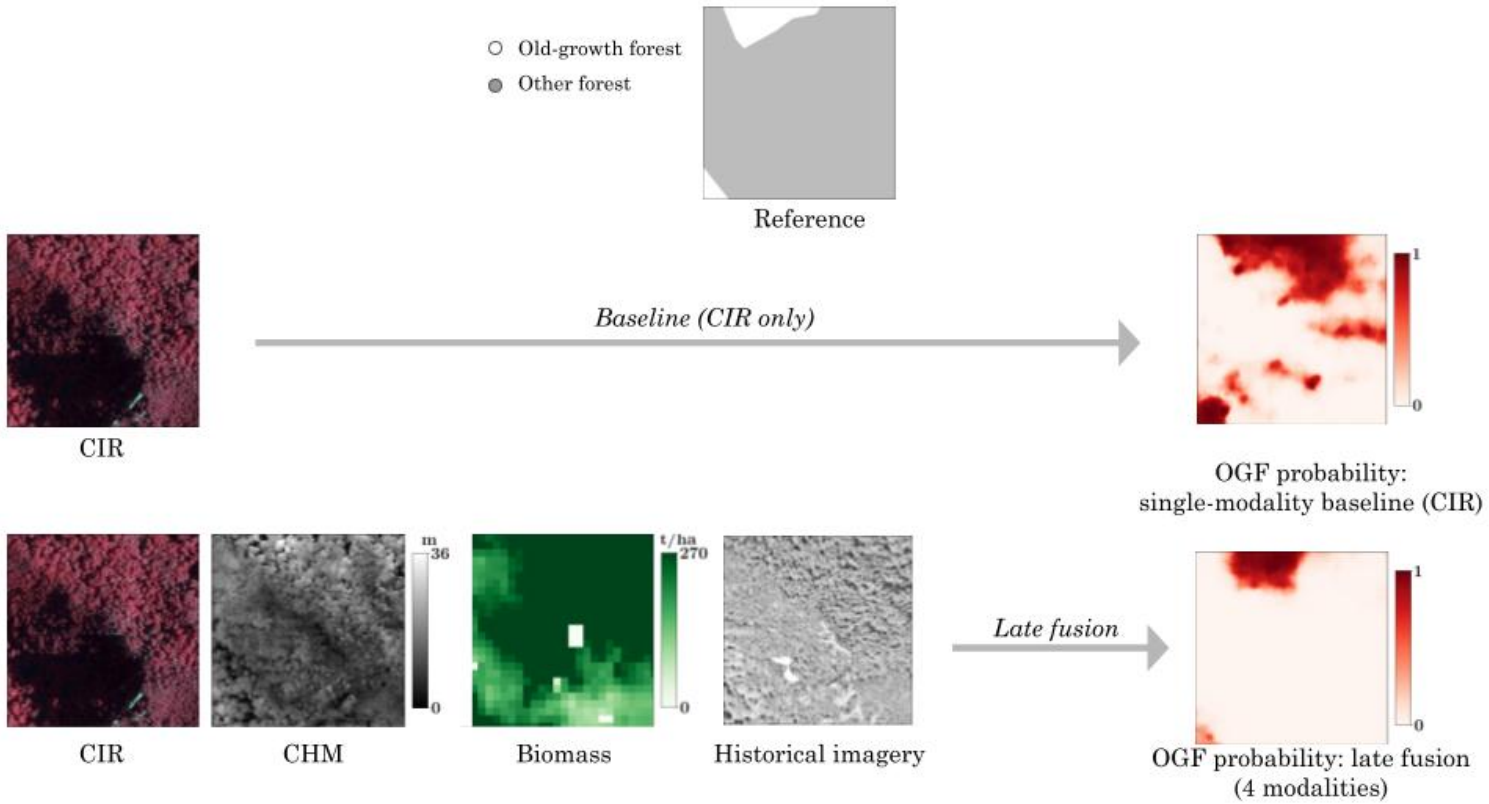
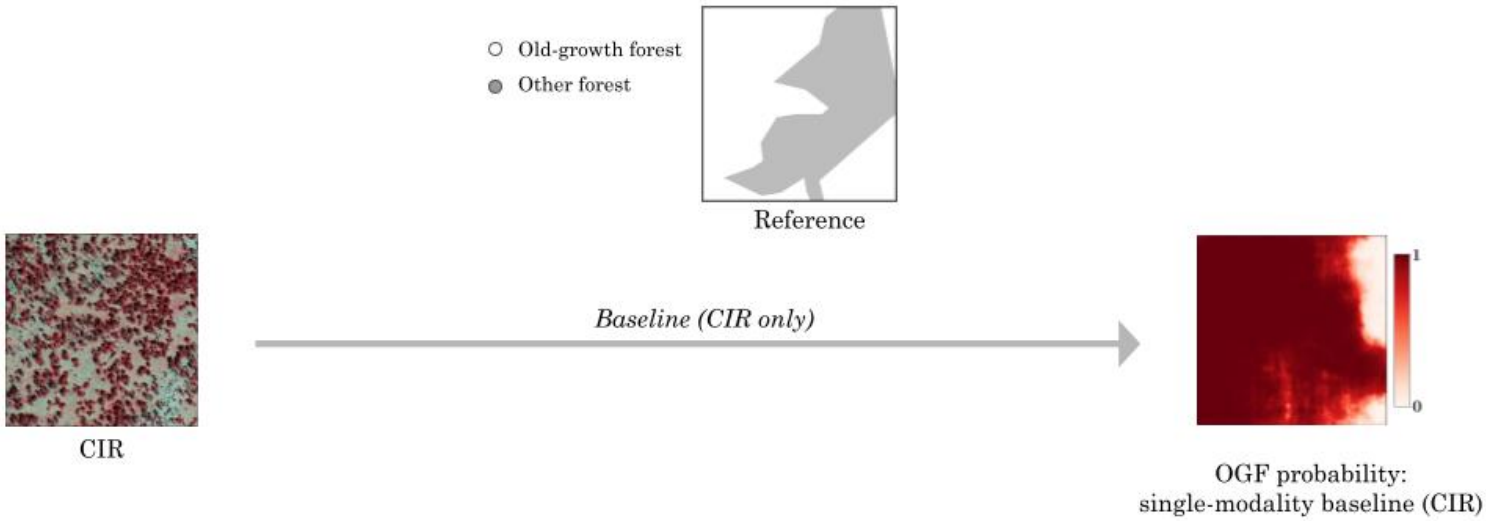


- Limit of IRC (passive sensor):
  shadows in mountain hollows → loss of signal
- The model can rely on other modalities
- In particular the CHM from LiDAR (active sensor)

Prediction examples: the contribution of historical imagery



- The whole area is forest
  → forest and old-growth look the same

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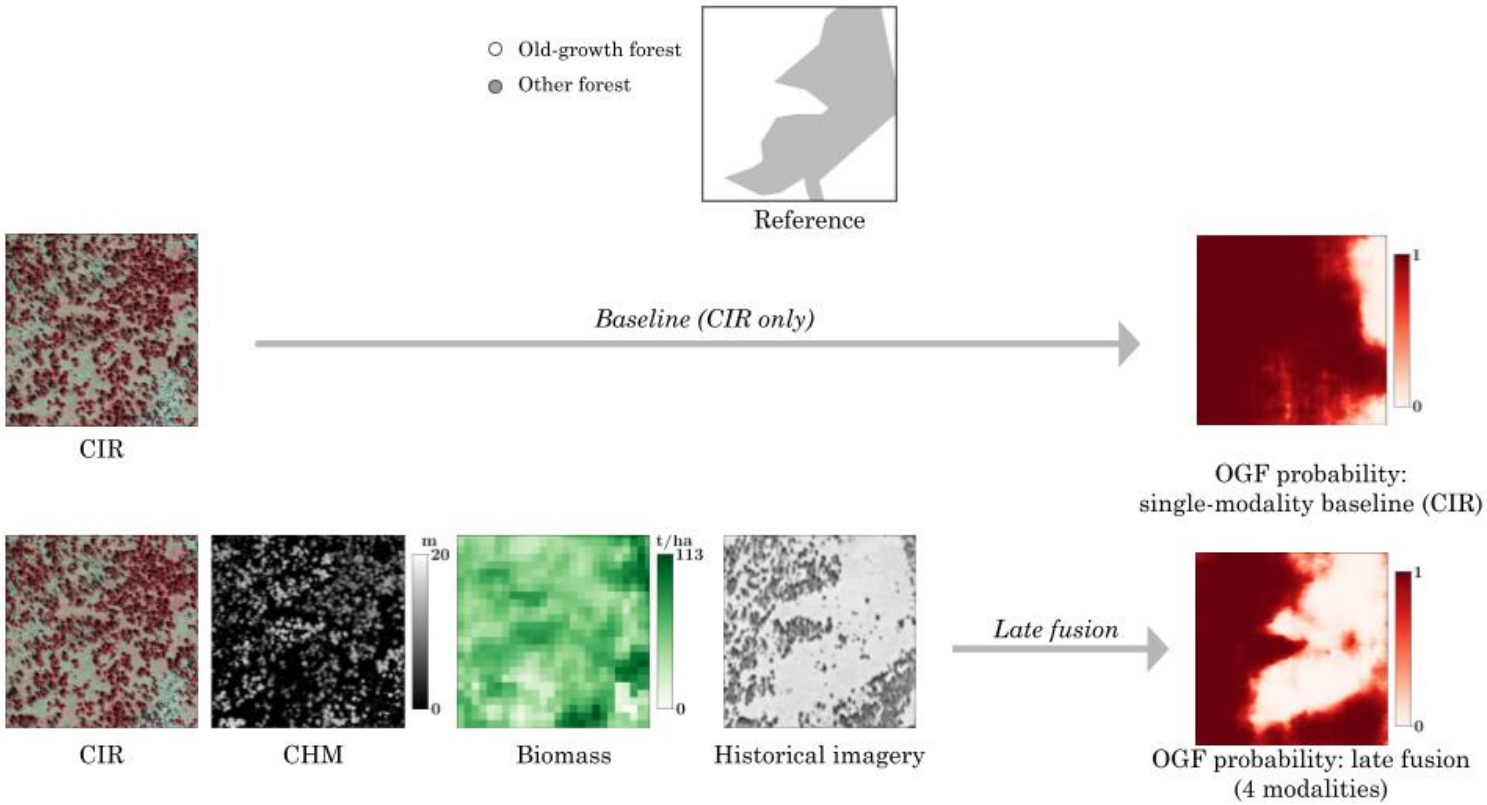
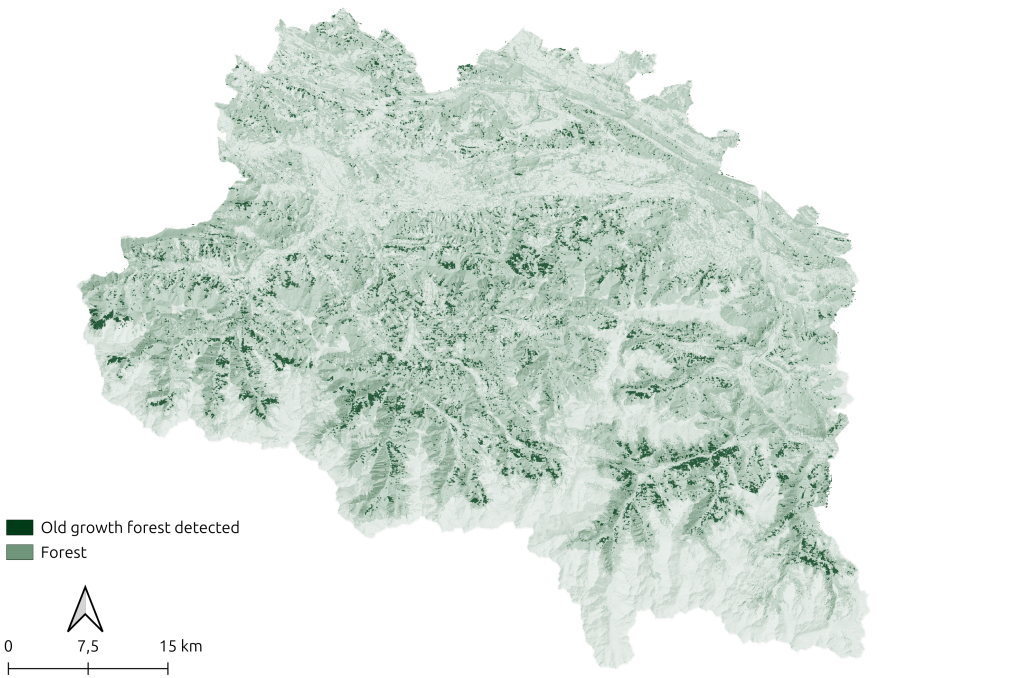


- The whole area is forest
  → forest and old-growth look the same
- Historical image
  → the model can distinguish forest from old-growth

Results on the Ariège Regional Natural Park



- The model over-detects, likely due to a lack of negative examples during training
- Predictions remain spatially consistent with potential biodiversity index maps (Collard et al., 2026)
- A promising starting point for old-growth forest mapping

Perspectives

Short term

- Rebalance the dataset: add more true negatives (non-OGF forest) to reduce over-detection

Long term

- Self-supervised learning to build pixel-level embeddings from CIR and LiDAR (DUNIA-style)
- Add the temporal dimension to detect forest changes over time
- Explore the explainability of multimodal models: better understand how the modalities contribute

Thank you for your attention

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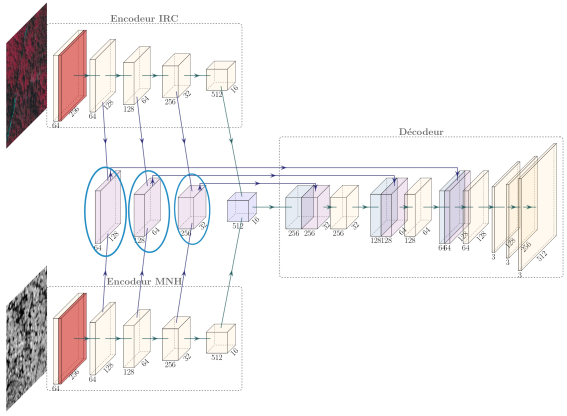
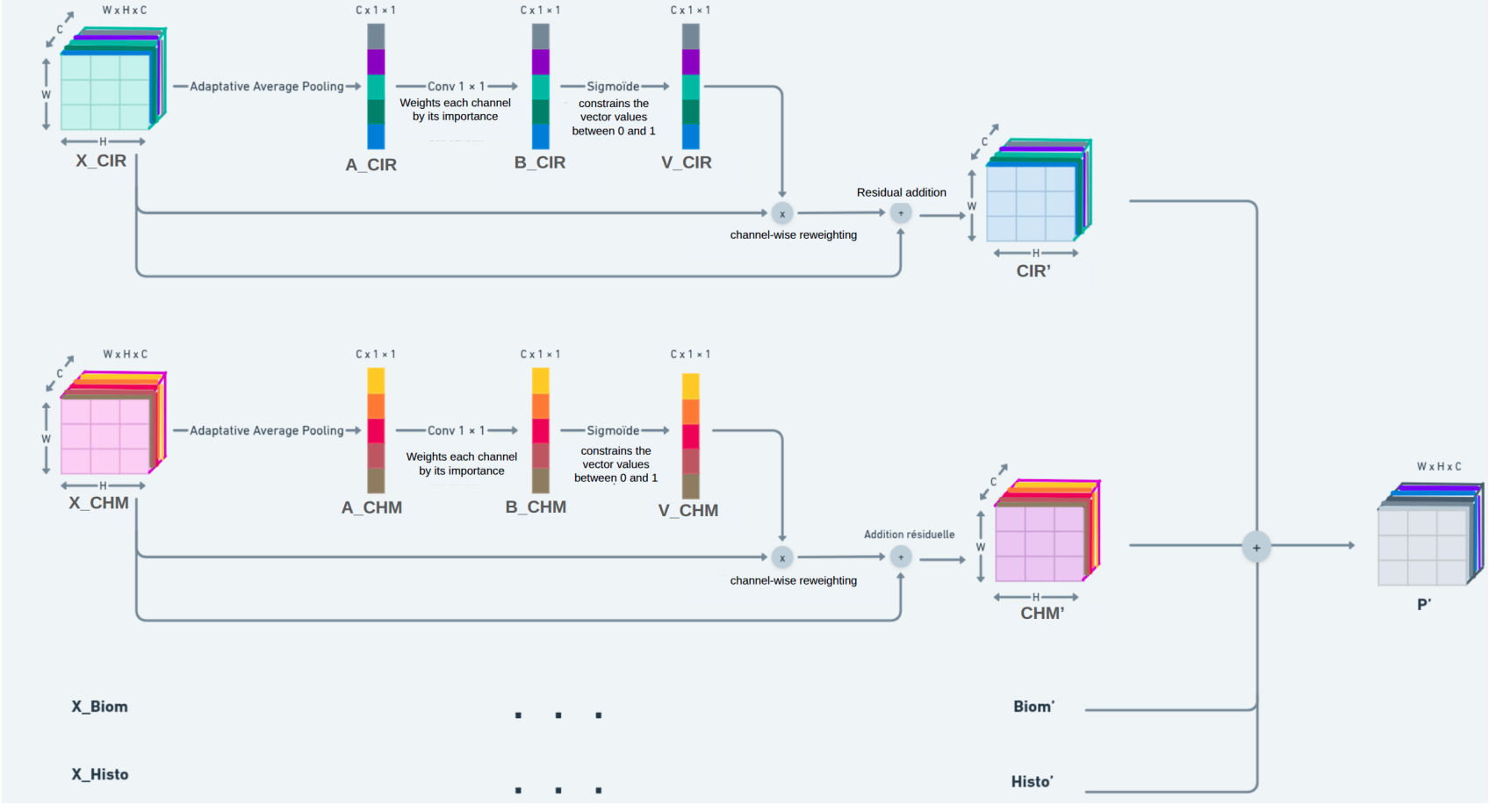
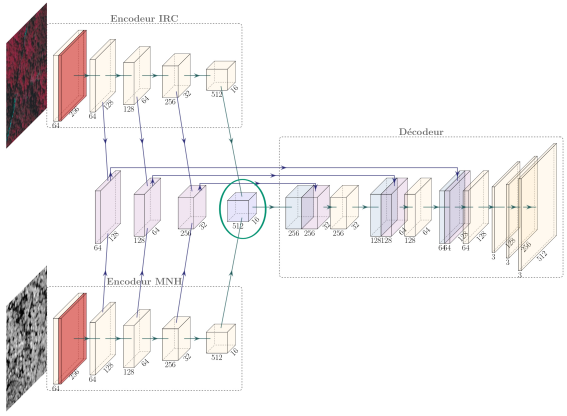

Encodeur IRC
Décodeur
Encodeur MNH


W x H x C
C
W
H
X_CIR
Adaptative Average Pooling
C x 1 x 1
A_CIR
Conv 1 × 1
Weights each channel by its importance
B_CIR
Sigmoïde
constrains the vector values between 0 and 1
V_CIR
channel-wise reweighting
Residual addition
CIR'
X_CHM
A_CHM
B_CHM
V_CHM
Addition résiduelle
CHM'
P'
X_Biom
Biom'
X_Histo
Histo'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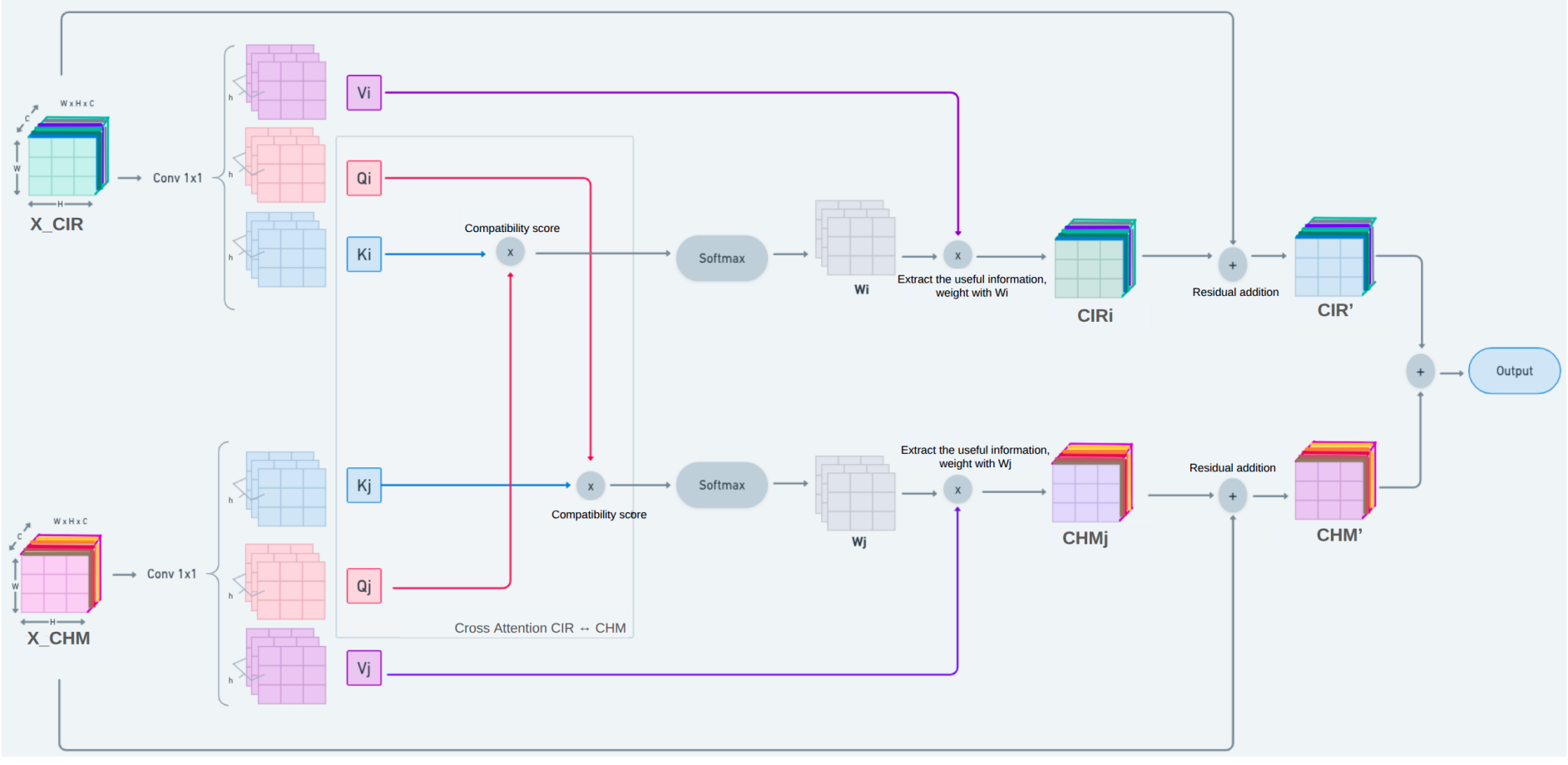
W x H x C
C
W
H
X_CIR
Conv 1x1
h
Vi
Qi
Ki
Compatibility score
x
Softmax
Wi
Extract the useful information, weight with Wi
CIRi
Residual addition
CIR'
+
Output
W x H x C
C
W
H
X_CHM
Conv 1x1
h
Kj
Qj
Vj
Compatibility score
x
Softmax
Wj
Extract the useful information, weight with Wj
CHMj
Residual addition
CHM'
Cross Attention CIR ↔ CHM

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