New methods and the importance of monitoring global biodiversity

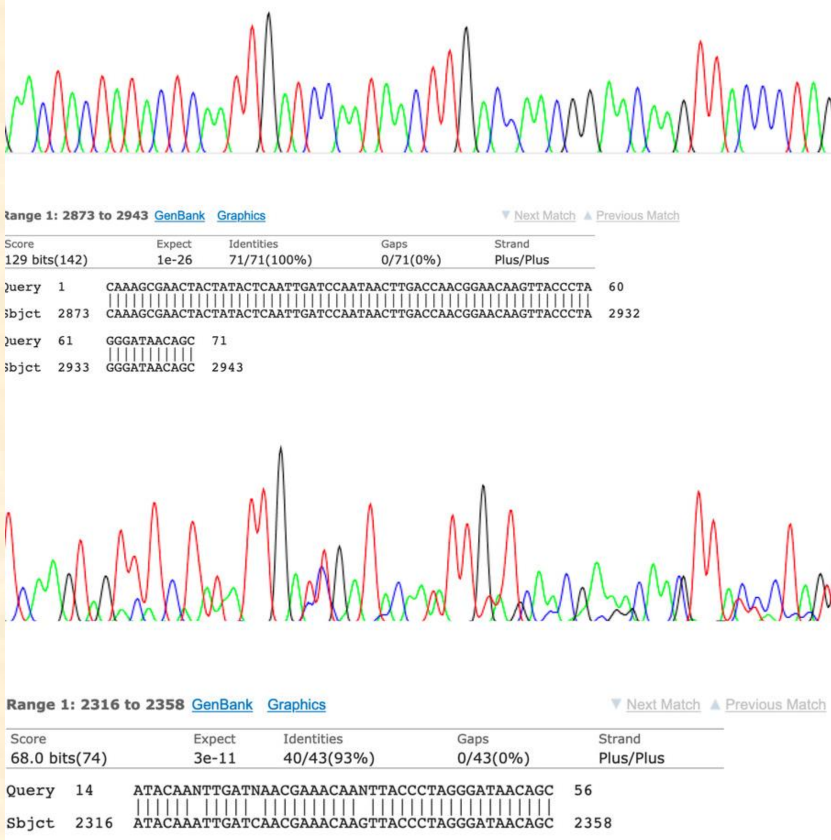
Environmental Impacts on Health and Disease

Multidisciplinary theme summer school

Dr Joanne Littlefair

Session outline

- The importance of global biodiversity
- Biodiversity loss
- Monitoring goals and methods
- Challenges and emerging novel solutions
- Case study 1: Environmental DNA (eDNA)
- Case study 2: Camera traps and machine learning



Molecular biodiversity monitoring

Human-mediated ecological change

Bioinformatics methods development and validation

What is biodiversity?

The diversity of all life forms: animals, plants, fungi and microorganisms, and all their interactions

The importance of global biodiversity

- Take five minutes with the person next to you to discuss any conclusions about the importance of biodiversity that you have taken away from the course so far.
- Include your own background knowledge if you are able to.

Follow on:

- Can the reasons for importance ever be ranked? How would different groups assign importance to biodiversity?

The importance of global biodiversity

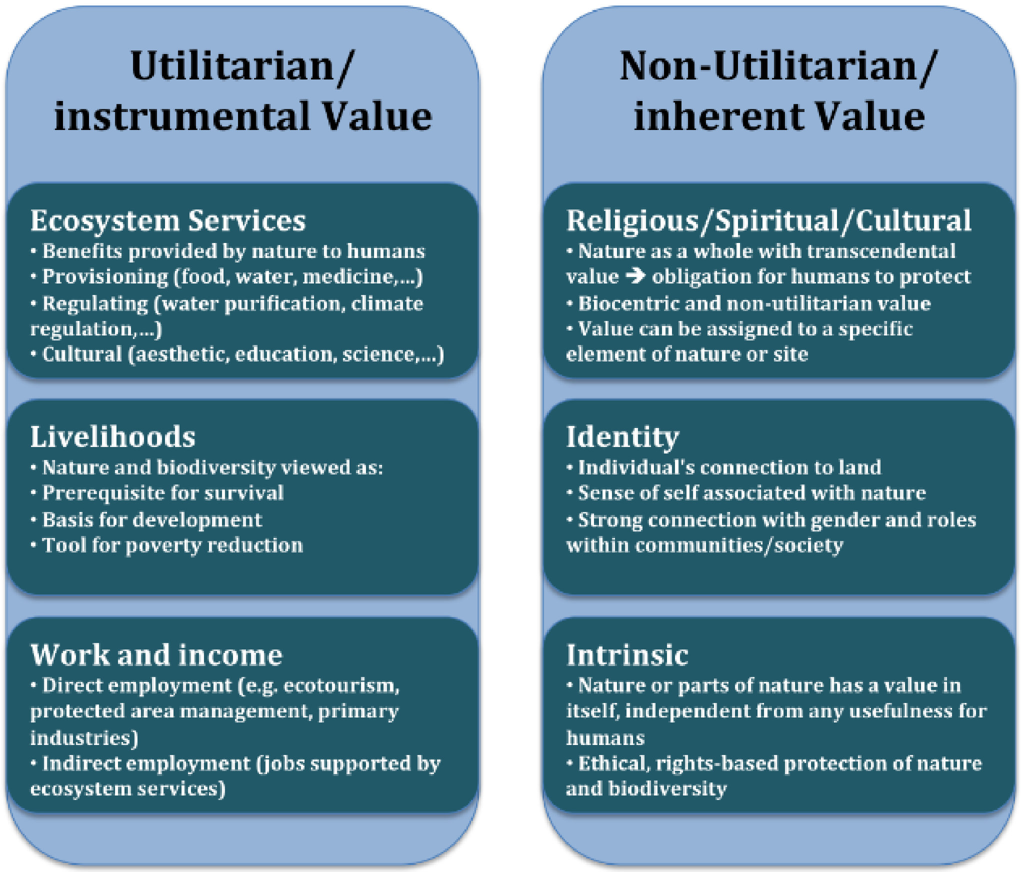
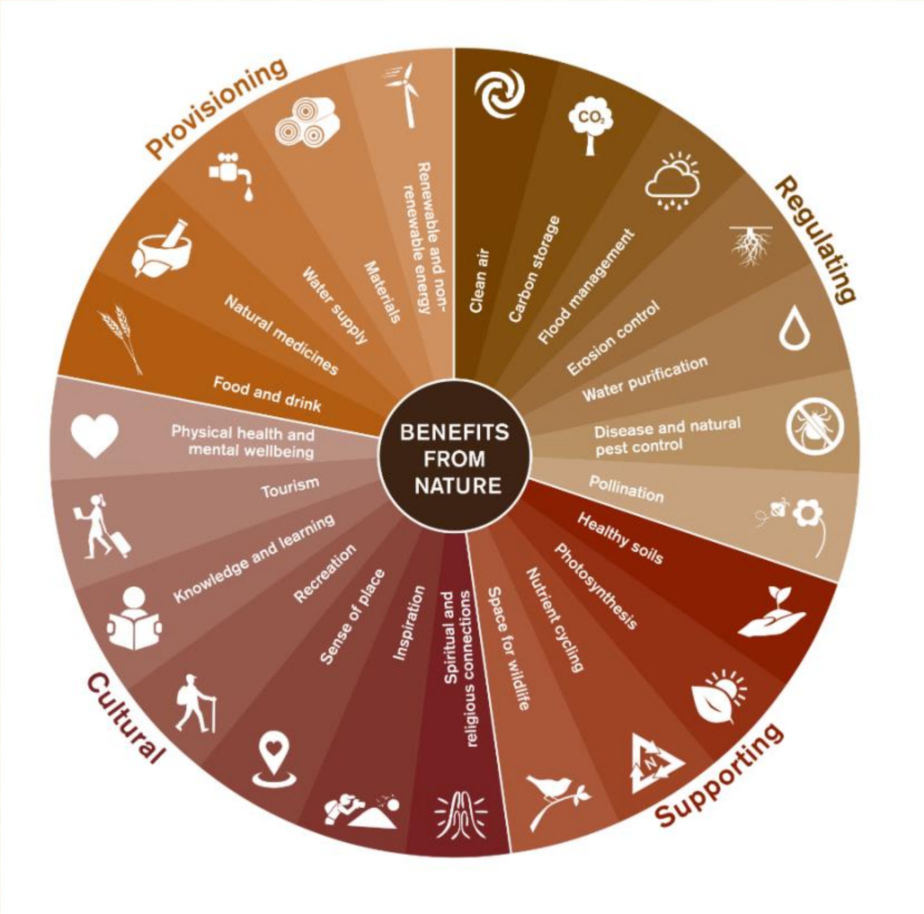


Figure 1: Dominant narratives of biodiversity and human wellbeing

- Bioethicists describe **intrinsic** and **instrumental** values of biodiversity.
- Intrinsic: organisms have an inherent value in and of themselves
- Instrumental: values received by humans that are a means to an end. Nature provides ecosystem services and natural resources.

Seddon et al. (2016) Biodiversity in the Anthropocene: Prospects and policy *PRSB*
Ecologic Institute (2015) Addressing multiple values of biodiversity in development cooperation *Policy brief*

Biodiversity & ecosystem services

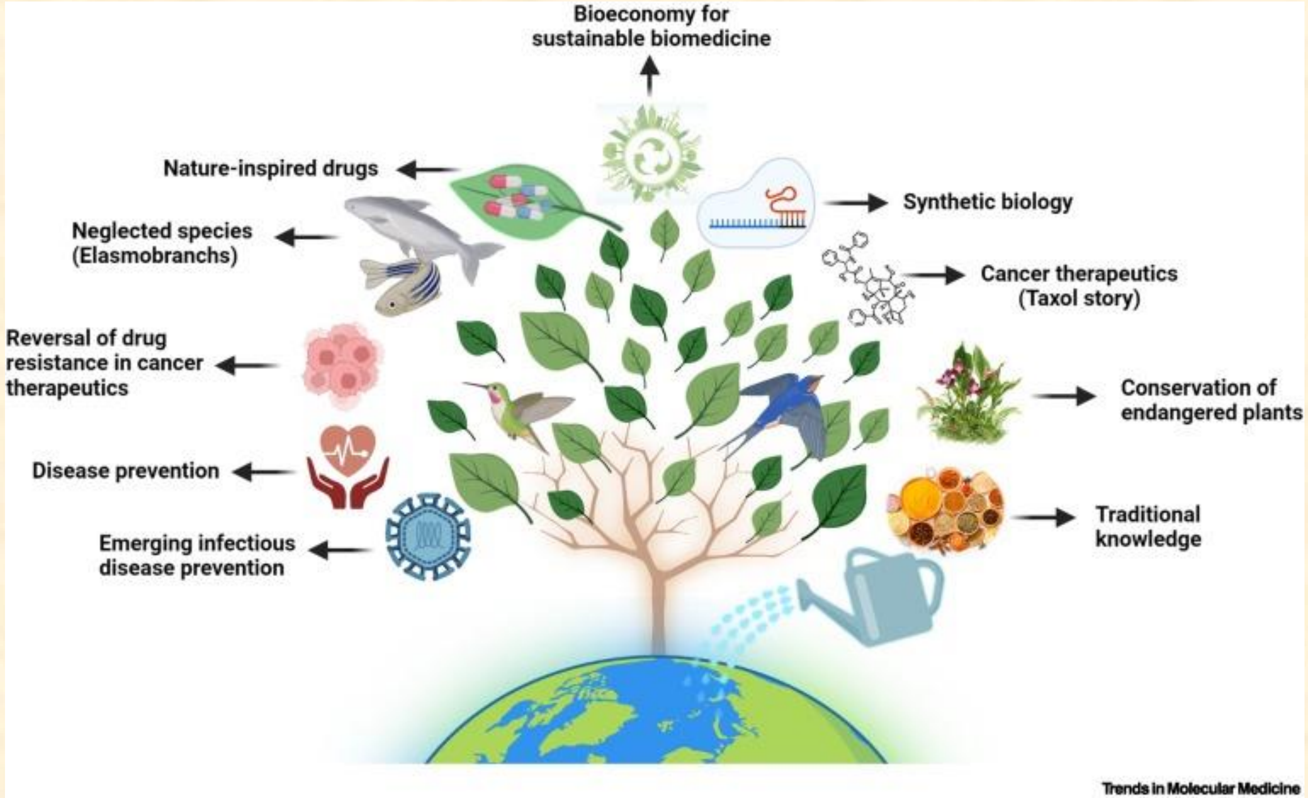


Benefits to humans are known as ecosystem services. On land, these encompass:

- Nutrient cycling
- Photosynthesis
- Food production
- Carbon sequestration
- Clean air
- Etc etc!

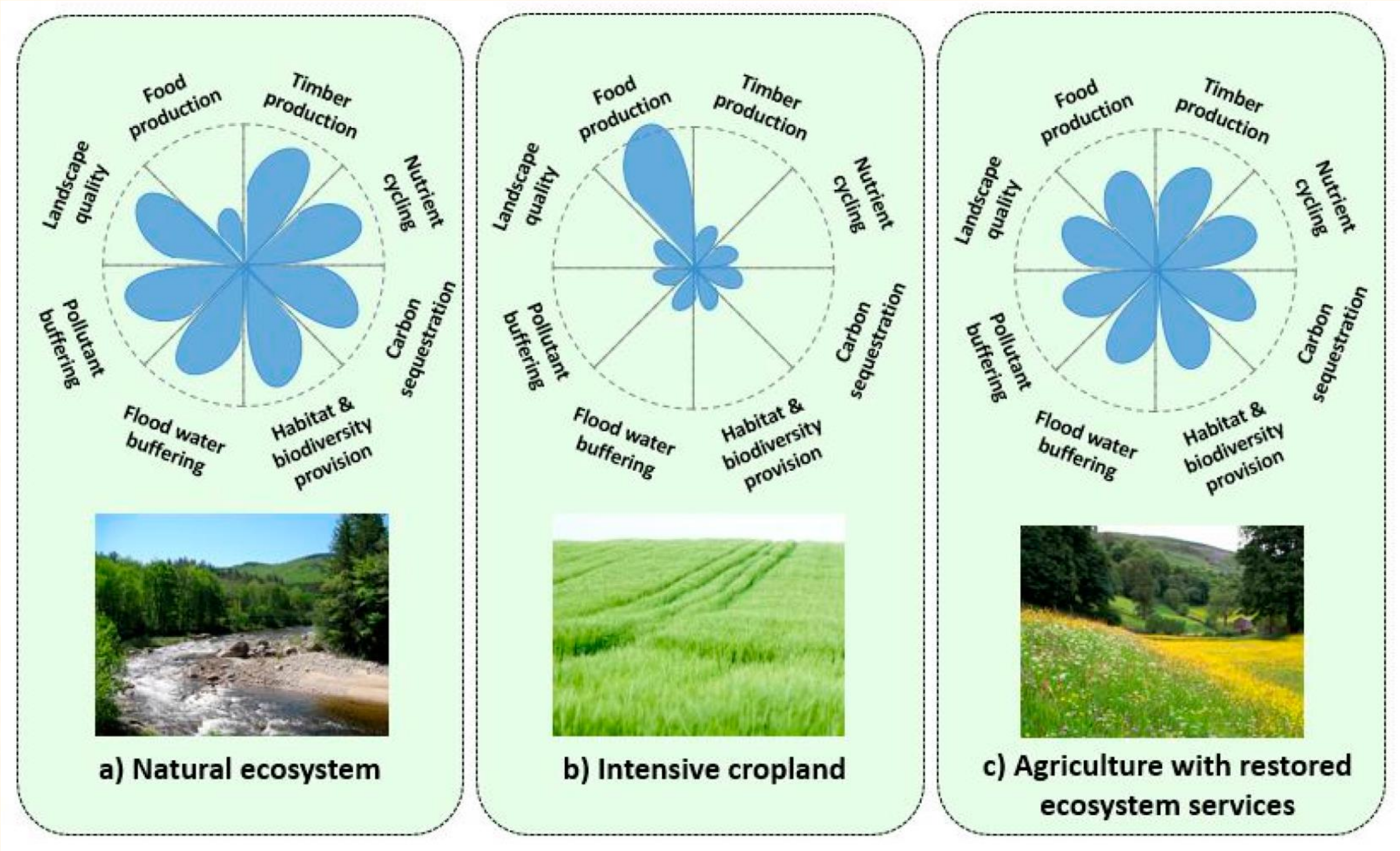
Image: NatureScot

The importance of global biodiversity



Linhares et al. (2023) Biodiversity: the overlooked source of human health *Trends in Molecular Medicine*

More biodiversity is linked to greater function



Stosch et al. (2017) Managing Multiple Catchment Demands for Sustainable Water Use and Ecosystem Service Provision *Water*

Ecocentric view

"These things [species] count, whether or not there is anybody to do the counting" (Rolston 1986).

"Species have value in themselves, a value neither conferred nor revocable, but springing from a species' long evolutionary heritage and potential" (Soule 1985).

"[Species] may not be valuable in themselves but they certainly may be valued for themselves. According to this…account, value is, to be sure, humanly conferred, but not necessarily homocentric" (Callicott 1989).

"[E]very species counts as having the same value in the sense that, regardless of what species a living thing belongs to, it is deemed to be prima facie deserving of equal concern and consideration...[Its good is] worthy of being preserved and protected as an end in itself and for the sake of the entity whose good it is" (Taylor 1986).

"[E]ndangered species are objectively valuable kinds, good in themselves; they do have their own welfare. Respect for life ought to be directly based on this value" (Rolston 1986).

Ecocentricist would consider intrinsic values:

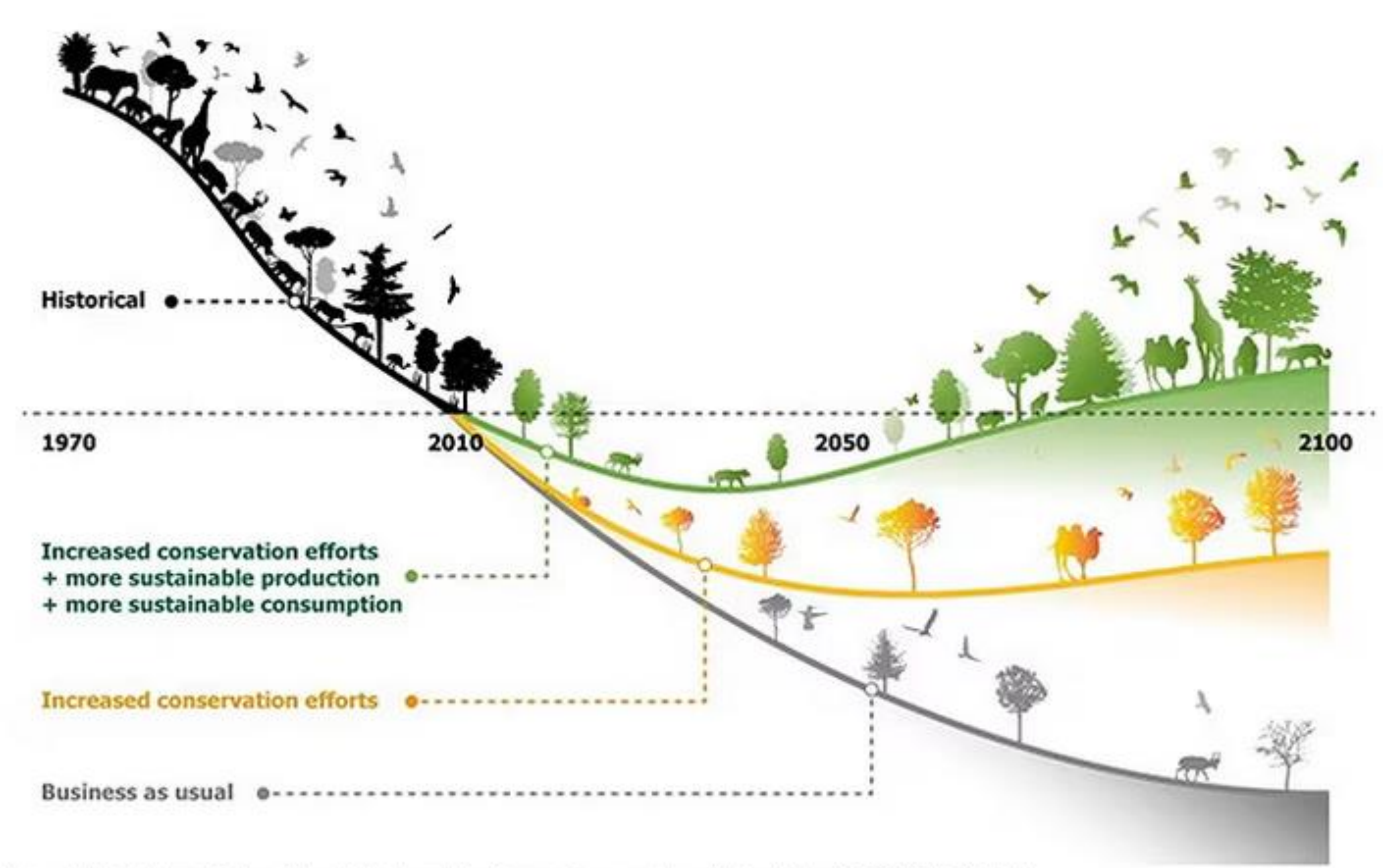
- Wildness & beauty
- Spiritual significance
- Evolutionary history
- Evolutionary potential
- Inherently deserving

Biodiversity loss

The WWF Living Planet Report describes global population losses of 69%.

Freshwater ecosystems are the most heavily impacted with 83% population loss since 1970.

We need to “bend the curve” of biodiversity loss.



This artwork illustrates the main findings of the article, but does not intend to accurately represent its results (https://doi.org/10.1038/s41586-020-2705-y)

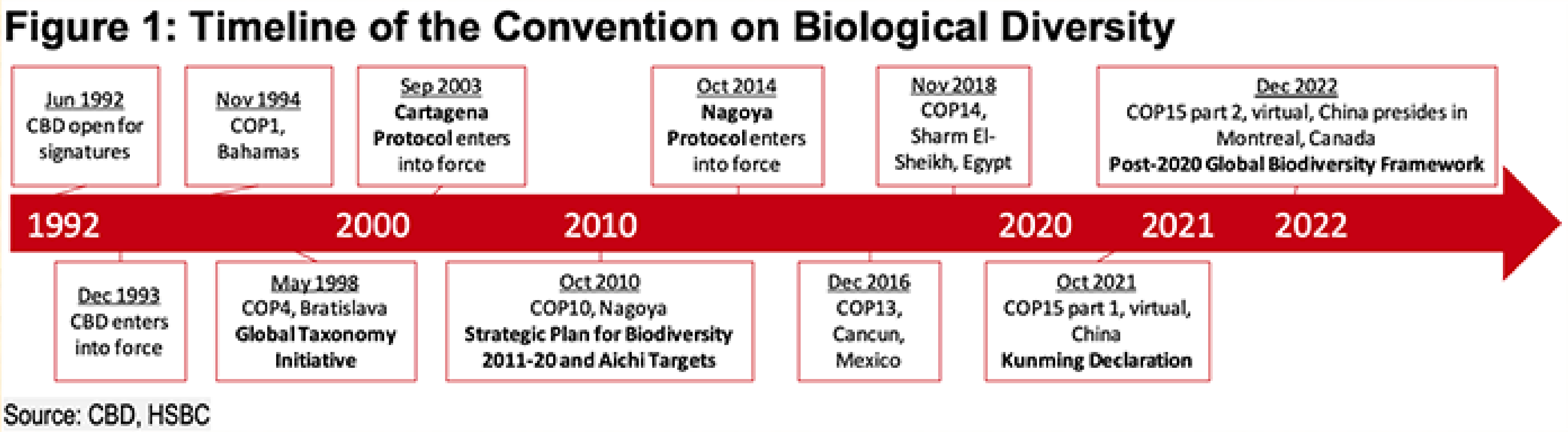
Biodiversity monitoring

Many different actors engage in biological monitoring:

- International agreements
- National laws
- NGOs
- Citizen scientists
- Commercial applications

RSPB

Biodiversity & governance



Current approaches to biomonitoring

- Broad surveys (government led). Indicator species.
- Citizen science (apps)
- In reaction to new development (commercial EIA)
- Some taxa or habitats are targeted through specialist directives: e.g., Water Framework Directive, bats, large mammals

Butterfly Conservation's BIG BUTTERFLY COUNT

Image credit: Justin Hofman

Are we monitoring well?

The inability to detect species and measure population dynamics rapidly and accurately is a fundamental challenge to our ability to meet biodiversity and conservation targets

A UN Sustainable Development Goal

In the UK

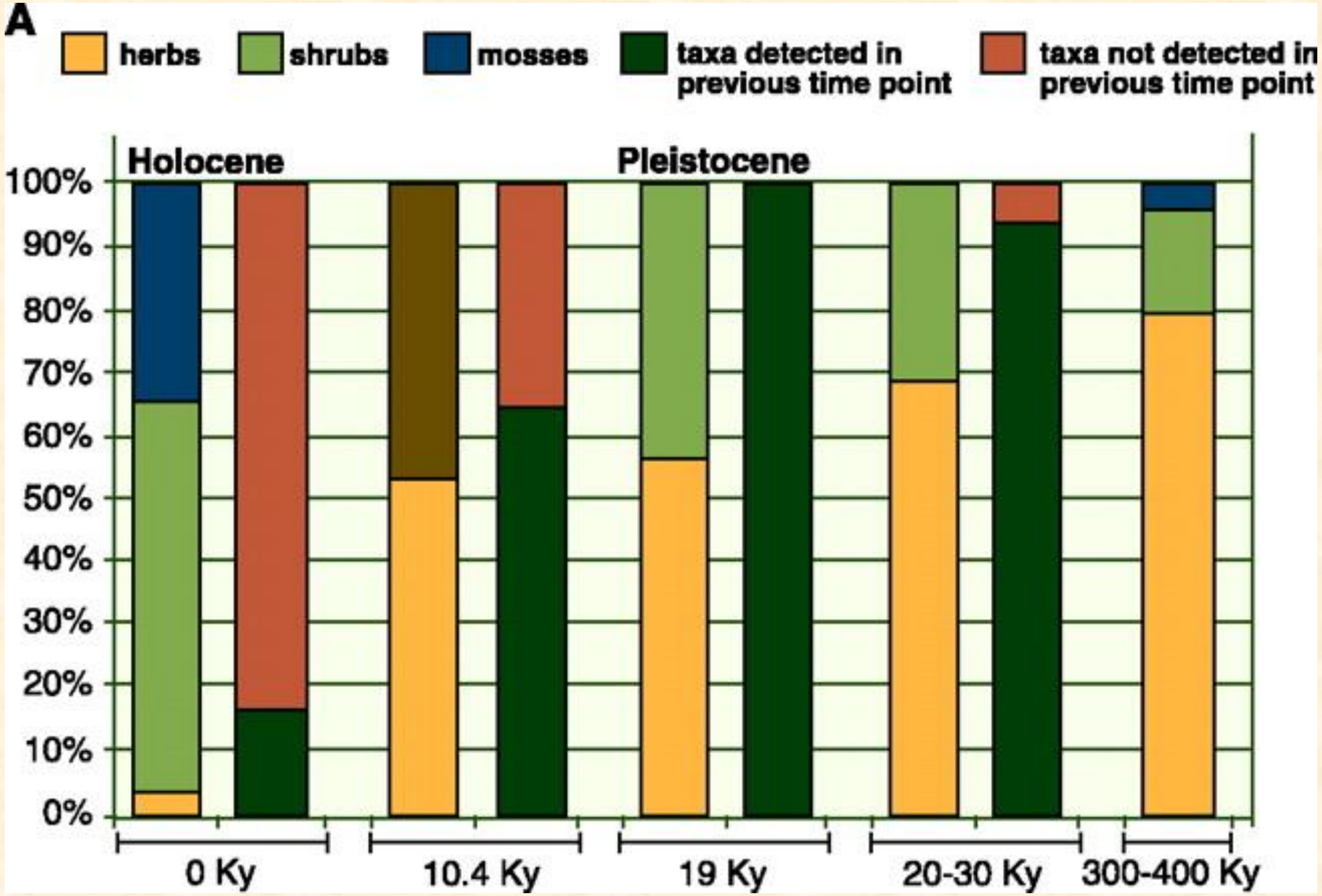
“an alarming lack of knowledge about the current state of the sites and the most vulnerable species in the UK”

Biodiversity in the UK: bloom or bust? House of Commons Environmental Audit Committee First Report of Session 2021–22.

Novel technologies for monitoring

If we were going to design an ideal method for collecting information on biodiversity, what would our requirements be?

Case study 1: Environmental DNA (eDNA)

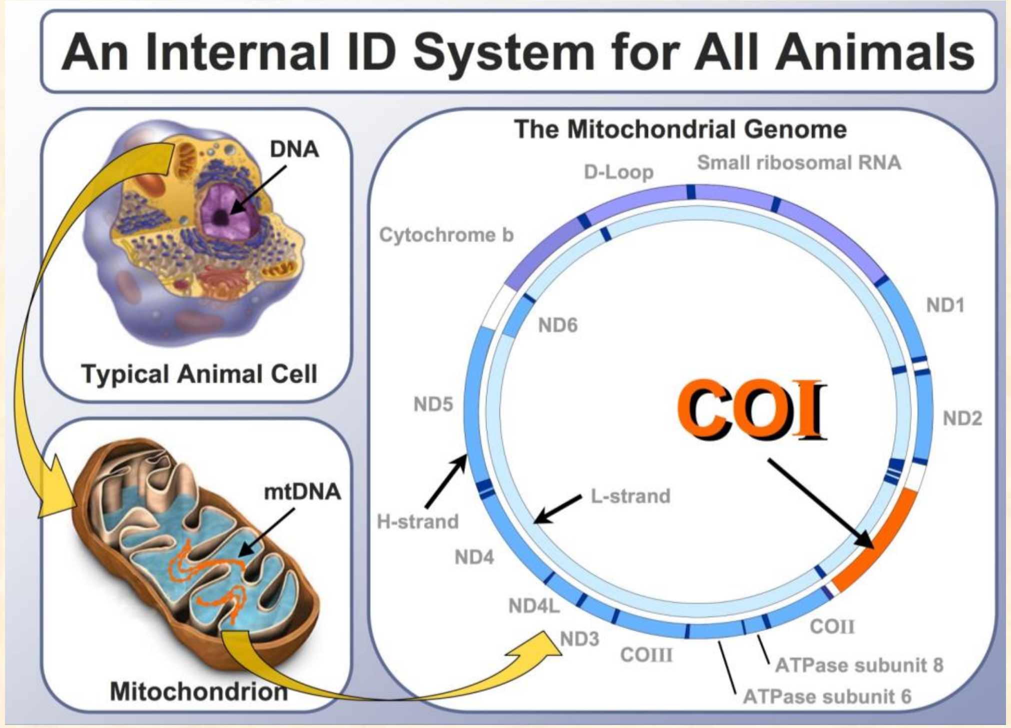


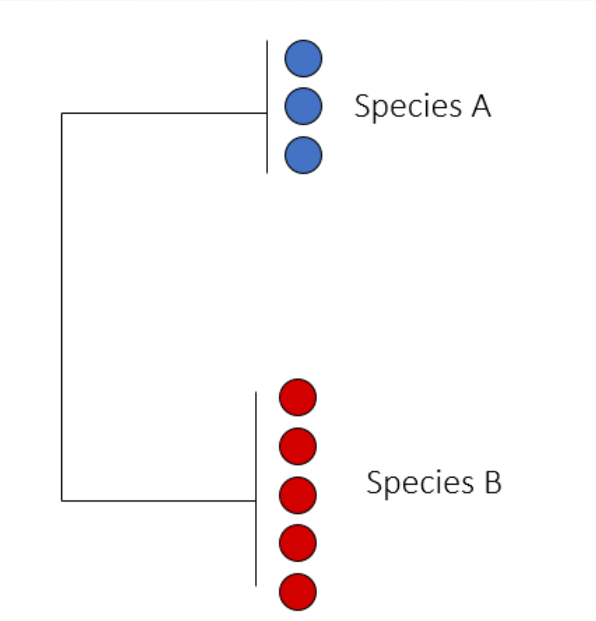
- Change in plant composition and diversity through time in permafrost core samples

Willerslev, E., Hansen, A. J., Binladen, J., Brand, T. B., Gilbert, M. T. P., Shapiro, B., … Cooper, A. (2003). Diverse Plant and Animal Genetic Records from Holocene and Pleistocene Sediments. *Science*, *300*(5620), 791–795. doi:10.1126/science.1084114

Environmental DNA (eDNA)

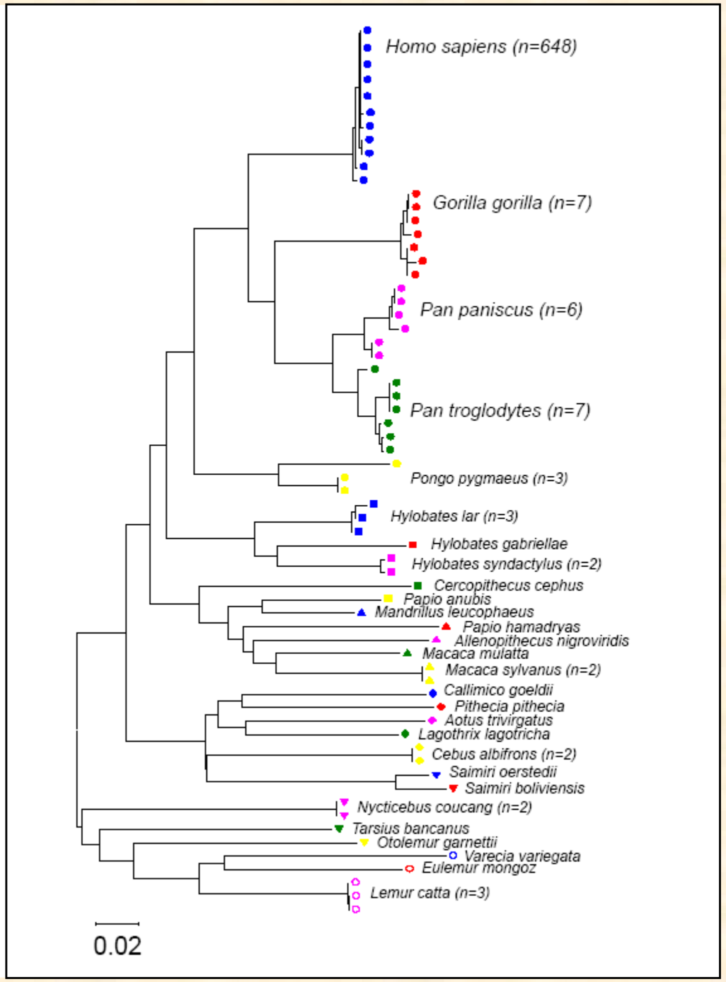
How can we read DNA?



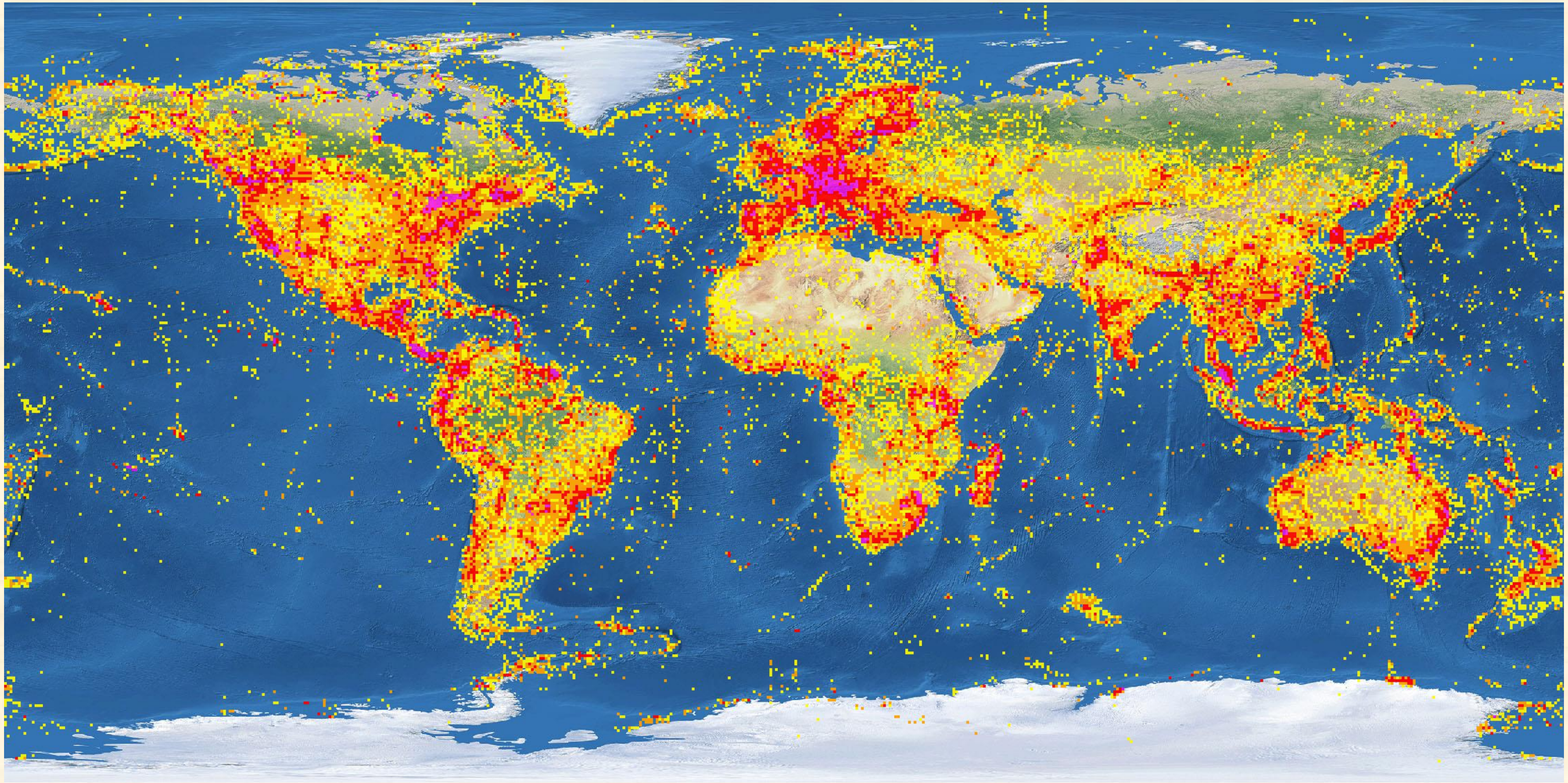


Intraspecific diversity is less than interspecific diversity

Species recognized by distinct barcode arrays (unique haplotypes)



The DNA library: 16.2m sequences

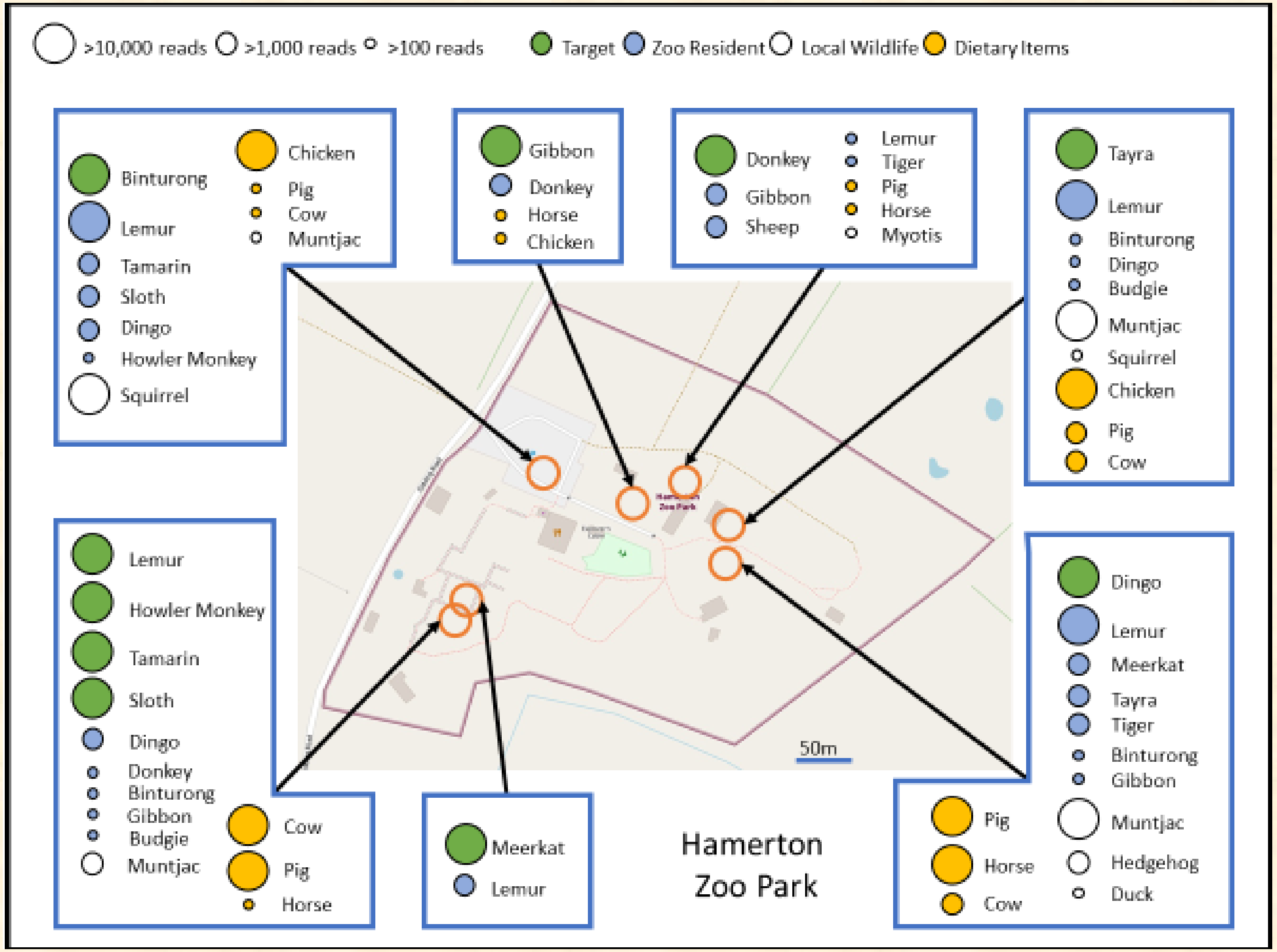


New research: airborne eDNA

- Approaches for aquatic habitats have been well developed since 2010s. Now widely used.
- Yet no approaches developed for the terrestrial biome.
- We developed a new approach sampling DNA from the air.

Clare *et al.* Current Biology (2022)

New research: airborne eDNA

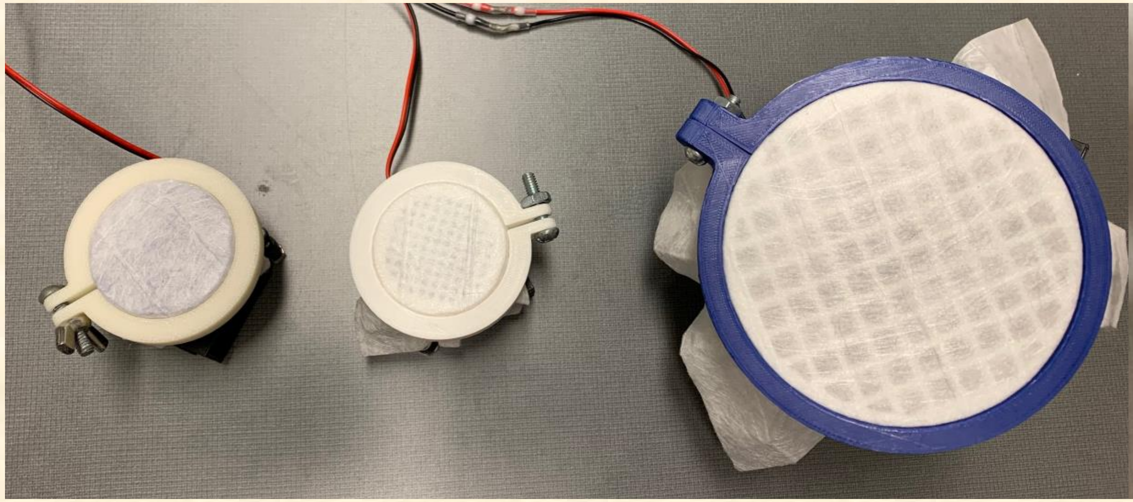


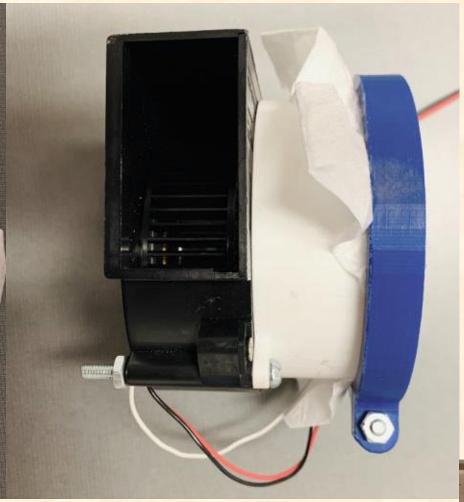
Clare *et al.* Current Biology (2022)

Application to species-at-risk

- Protected species under UK and international legislation
- COVID-19 and other EIDs
- Structural stability of roosts
- Morphological ID can be challenging
- Airborne DNA worked best in enclosed spaces

Enclosed spaces: roosts and caves



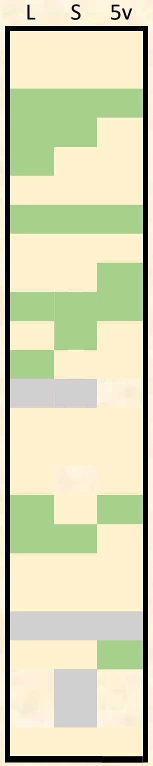


Work led by Nina Garrett, York University Canada

Enclosed spaces: roosts and caves

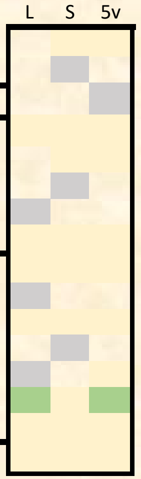
From the “roost”

Emballonuridae	*Saccopteryx*	*Saccopteryx bilineata* (**Greater white-lined bat**)
	Artibeus	*Artibeus jamaicensis* (**Jamaican fruit-eating bat**)
Phyllostomidae		*Artibeus lituratus/intermedius* (**Great fruit-eating bat**)
	Carollia	*Carollia perspicillata* (**Seba's short-tailed bat**)
	Dermanura	*Dermanura phaeotis* (**Pygmy fruit-eating bat**)
	Desmodus	*Desmodus rotundus* (**Common vampire bat**)
	Glossophaga	*Glossophaga mutica* (**Common long-tongued bat**)
	Lophostoma	*Lophostoma evotis* (**Davis' round-eared bat**)
	Phyllostomus	*Phyllostomus discolor* (**Pale spear-nosed bat**)
	Strunira	*Sturnira parvadens* (**Little yellow-shouldered bat**)
	Trachops	*Trachops cirrhosis* (**Fringe-lipped bat**)
	Uroderma	*Uroderma convexum* (**Common tent-making bat**)
	Vampyressa	*Vampyressa thyone* (**Little yellow-eared bat**)
	Eumops	*Eumops spp.* (**Bonneted bats**)
Molossidae	*Molossus*	*Molossus spp.* (**Mastiff bats**)
	Mormoops	*Mormoops megalophylla* (**Ghost-faced bat**)
Mormoopidae	*Pteronotus*	*Pteronotus fulvus* (**Dacy's naked-backed bat**)
		Pteronotus mesoamericanus (**Common mustached bat**)
	Natulus	*Natalus mexicanus* (**Mexican funnel-eared bat**)
Natalidae	*Noctillo*	*Noctilio (leporinus)* (**Greater bulldog bat**)
Noctilionidae	*Bauerus*	*Bauerus dubiaquercus* (**Van gelder's bat**)
Vespertilionidae	*Eptesicus*	*Eptesicus (furinalis)* (**Argentine brown bat**)
	Lasiurus	*Lasiurus ega* (**Southern yellow bat**)
	Myotis	*Myotis spp.* (**Myotis bats**)
	Rhogeessa	*Rhogeessa aeneus* (**Yucatán yellow bat**)



From the outside

Phyllostomidae	*Chrotopterus*	*Chrotopterus auratus* (**Whooly False Vampire Bat**)
Emballonuridae	*Rhynchonycteris*	*Rhynchonycteris naso* (**Proboscis Bat**)
Bufonidae	*Bufo*	*Bufo bufo* (**Common toad**)
Catelidae	*Alouatta*	*Alouatta palliata* (**Mantled howler monkey**)
Cricetidae	*Ototylomys*	*Ototylomys phyllotis* (**Big-eared climbing rat**)
Procyonidae	*Pottos*	*Potos flavus* (**Kinkajou**)
Sciuridae	*Sciurus*	*Sciurus yucatanensis* (**Yucatan squirrel**)
Tayassuidae	*Pecari*	*Pecari tajacu* (**Collared peccary**)
Bovidae	*Bos*	*Bos taurus* (**Cattle**)
	Capra	*Capra hircus* (**Goat**)
Canidae	*Canis*	(**Dog or related species**)
Equidae	*Equus*	*Equus caballus* (**Horse**)
Felidae	*Felis*	(**Cat or related species**)
Bovidae	*Ovis*	*Ovis aries* (**Sheep**)
Suidae	*Sus*	*Sus scrofa* (**Pig**)
Phasianidae	*Gallus*	*Gallus gallus* (**Chicken**)



Legend

Yellow = high quality detections
Green = Low quality detections
Grey = very low sequence counts
White = not detected

Garrett, N., …, Littlefair J.E., Clare E.L. Airborne eDNA documents a diverse and ecologically complex tropical mammal community *Environmental DNA*

Work with the Bat Conservation Trust

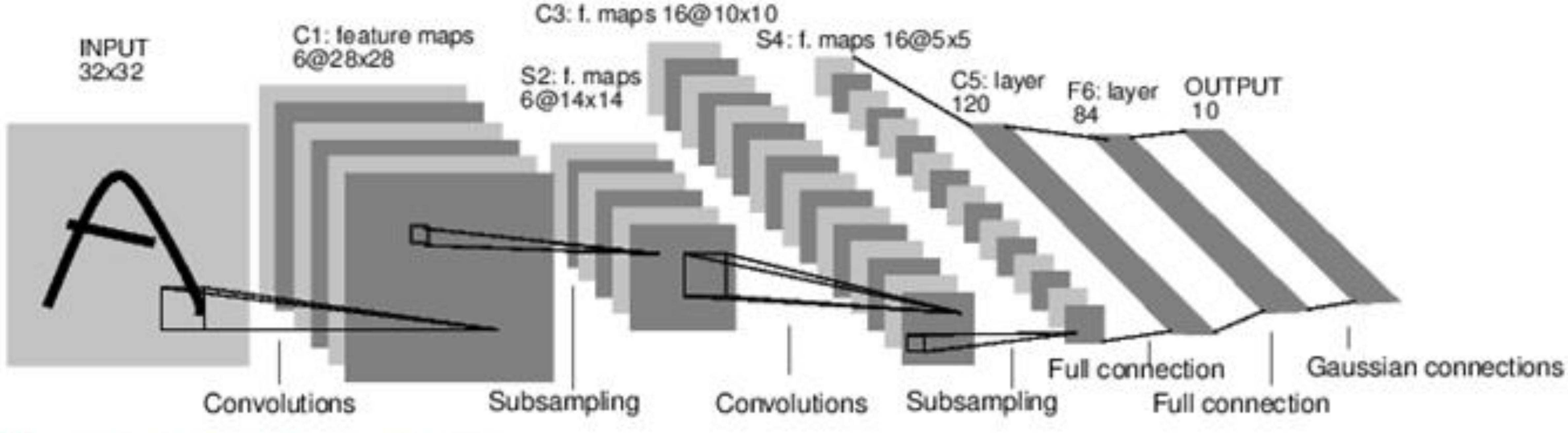
Can we detect UK bat species inside hibernacula?




Case study 2: camera traps and machine learning

<u>The need for image analysis</u>

- Chinko Conservation area, Central African Republic
- 100 camera traps generate 100,000-200,000 images per season



A full convolutional neural network (LeNet)

Convolutional neural networks

- Images contain vast and complex information
- Information is spatially correlated
- Neural networks use examples to automatically infer rules for recognizing images

CNNs look for key image properties

Malay civet, camera trap data collected from QM field trip to Borneo

“Edges” usually display useful information in image data

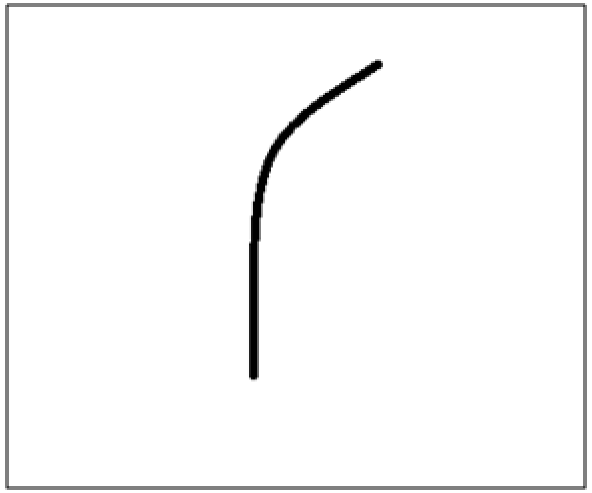
Groups of neurons fire when we see edges of a certain orientation

Hubel & Wiesel 1962

This information is encoded in pixels

Identifying key features

What does a “curve detector” look like computationally?



Visualization of a curve detector filter

0	0	0	0	0	30	0
0	0	0	0	30	0	0
0	0	0	30	0	0	0
0	0	0	30	0	0	0
0	0	0	30	0	0	0
0	0	0	30	0	0	0
0	0	0	0	0	0	0

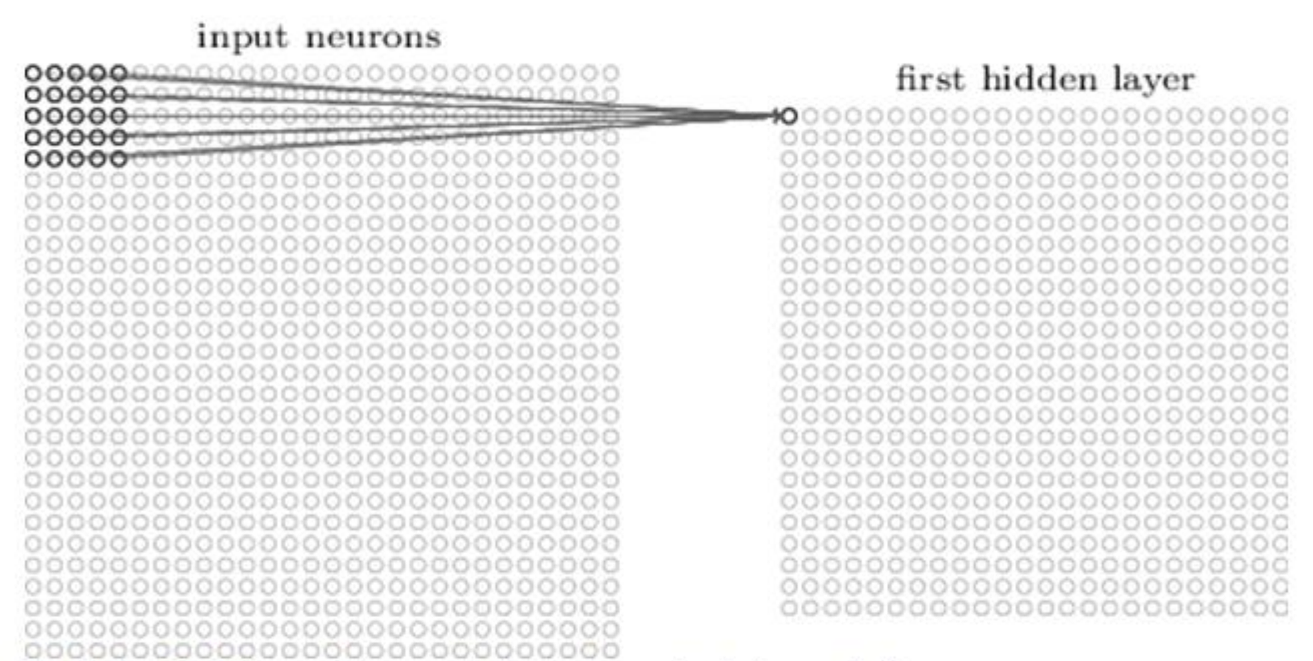
Pixel representation of filter

Different filters detect different shapes and lines

Image adapted from: “Neural networks and deep learning” Michael Nielsen

Convolutional layer

Receptive field Activation map



Visualization of 5 x 5 filter convolving around an input volume and producing an activation map

The **filter** is **convolving** (sliding) around the **receptive field** (input image)

Stride is the number of units the filter moves

The array of numbers in the filter is multiplied by the original pixel values in receptive field.

These are summed

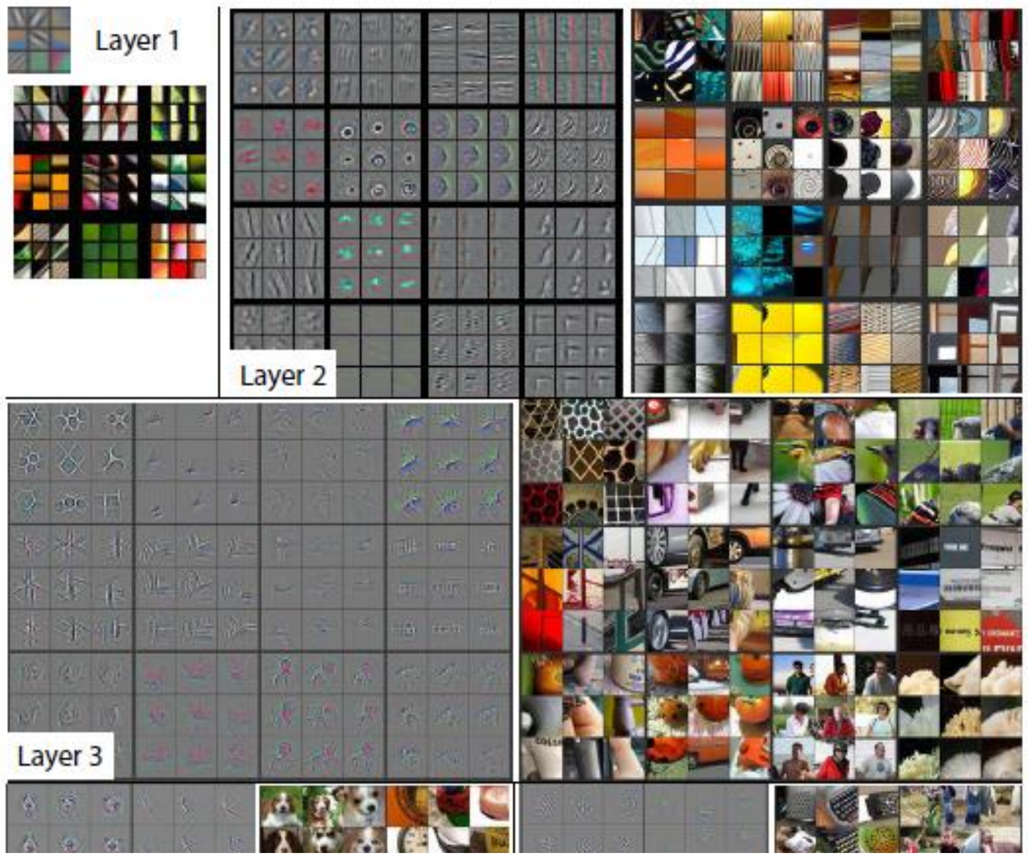
Image adapted from: "Neural networks and deep learning" Michael Nielsen

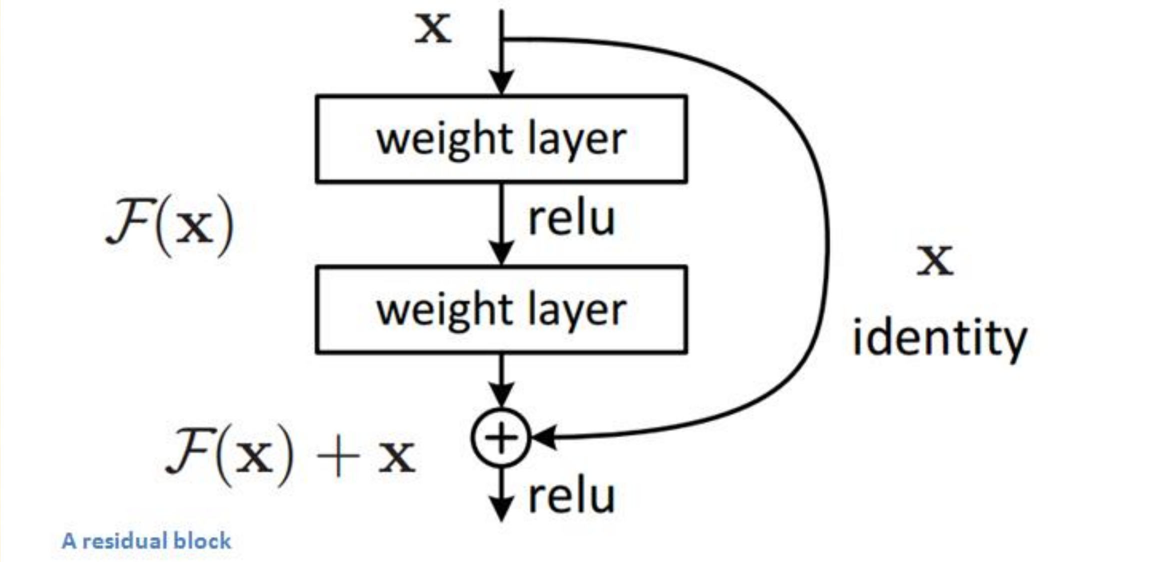
Multiple layers

- The second, third, fourth etc. layers look for higher order features.
- Filters have a larger receptive field in subsequent layers

<u>ReLU layers</u>

- Rectified Linear Units
- Introduce non-linearity after linear computations
- Applies function f(x) = max(0, x) to all values of input





Visualisation of filters in a fully trained CNN
Zeiler & Fergus 2014

Fully connected layer

- Uses the final layer as the input volume
- Outputs an N dimensional vector (softmax)
- N = number of classes that are available for the programme to choose from (e.g., bat, cat, dog etc.)
- Each number in the vector is a probability

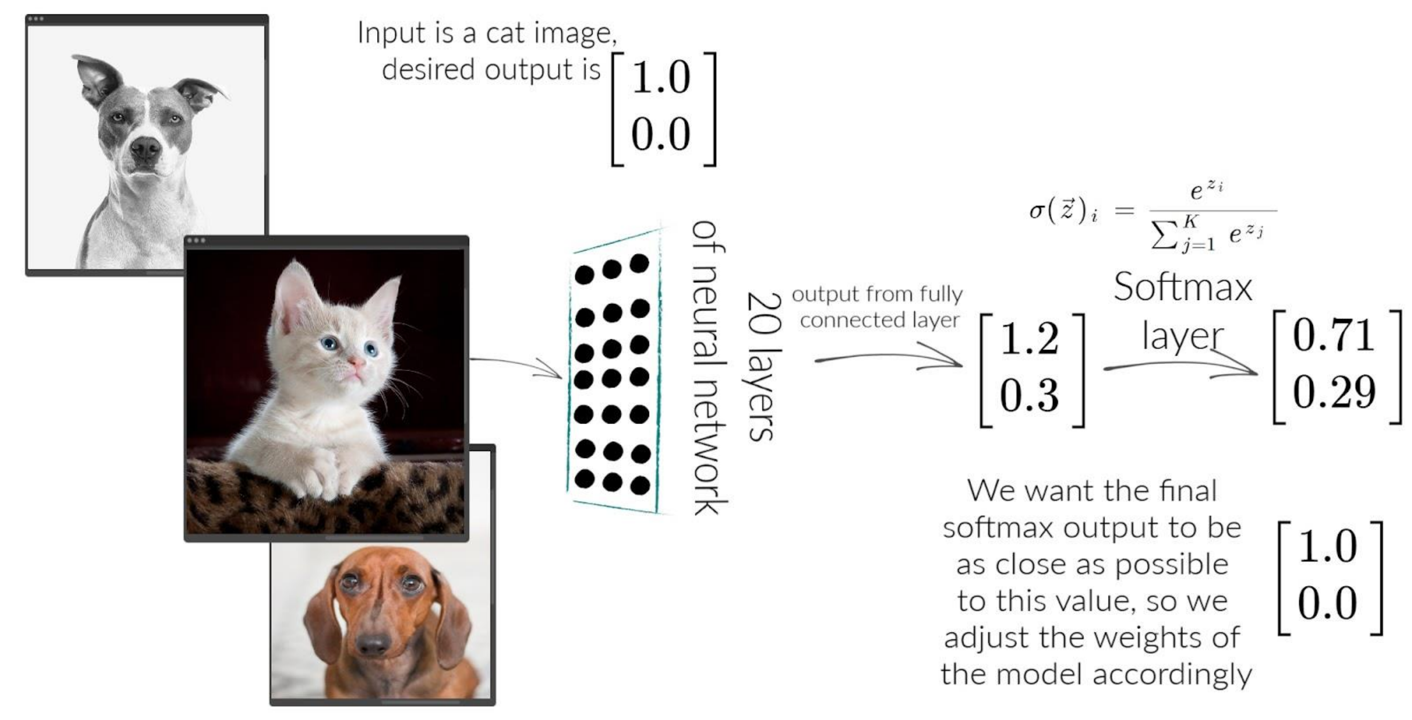


Image credit: deepAI

Training through backward propagation

- Before training begins, CNN does not know what features are important or which filters to apply.
- A training dataset composed of 10000s of labelled images is required.
- Backpropagation:
  - Forward pass
  - Loss function
  - Backward pass
  - Weights update

Issues with CNNs and image analysis

- Animals which are difficult to see
- Different image frame
- Multiple animals
- Background bias during training

Summary

- Biodiversity is central to all life and health but is disappearing at an unprecedented rate.
- The human resources burden of monitoring is extremely high, resulting in patchy data or focused only on key indicator species.
- Technologies that can develop into semi- or fully-autonomous solutions for sampling the whole community will widen our understand.