Automated species identification systems for landscape monitoring of biodiversity (ORTHOSOUND)

Applicants: *Prof. Loïc Pellissier*, ETHZ/WSL, *Prof. Pierre-André Farine* and *Dr. Sara Grassi*, EPFL.

Collaborators: *Matthias Riesen*, *Jürg Schlegel* (ZHAW, Project managers of the orthoptera app), *Christian Roesti*, *Florian Rutschmann* (Grasshopper experts and developers of orthoptera.ch).

1. Abstract

Background On-going climate change induces shifts in the distribution of species along latitude and elevation gradients, while land-use intensification is degrading the quality of habitats for biodiversity. Global changes are thus largely threatening existing semi-natural ecosystems. Monitoring data are required to design management strategies and limit the negative effects of global change on biodiversity. While automated measurement of abiotic components of landscapes are common (e.g. through meteorological stations) devices that automatically measure the biotic components of the landscape are almost inexistent.

Aim Automated Recording Systems (ARS) applied to continuous recording and detection of a group of species that are good bioindicators of ecosystem health would represent an advance for landscape management. The recent miniaturisation of many sensors, many of them being integrated in smartphones, would allow developing this technology. Here, we propose a novel ARS method to monitor automatically composition of orthoptera from sound and use this information for ecosystem monitoring. As a second goal, we will implement the algorithm in an existing smartphone application as a tool to promote citizen science and knowledge transfer.

Methods The project consists of three phases. 1) During the development phase and based on an existing database of orthopteran songs, we will extract a set of descriptors characterising the sound of each species. Using several sound analysis and machine learning approaches, we will train the models to discriminate species and validate the approach with cross-validation. 2) During the deployment phase, we will collect sound data of grasshopper assemblages from a recorder station in 20-30 sites and test whether the software is able to detect the species present. 3) During the implementation phase, we will implement the software into a smartphone application associated to a data server.

Funding requested Funding is requested for one PhD student for three years, for one postdoc for two years, 3 months of a field entomologist and 6 months of a software engineer. The cost of electronic material will be provided by matching funds from ETHZ/WSL.

Expected value of the proposed project The project will bring a novel tool to monitor biodiversity in the landscape. In addition, the project aims at using this knowledge on the spatial variation of a good indicator taxon to improve our understanding of the species distributions in the landscape. It will provide an assessment of the expected impact of climate and land use changes on biodiversity. By implementing our technique in a smartphone application, this tool will be made available for citizen collection of biodiversity data.

Keywords: climate change, land use change, smartphone application, grasshoppers, biodiversity, ecological niche models, species distribution, insect sound recognition, Switzerland.

2. Research plan

2.1 State-of-the-Art

Biodiversity can be summarized as the "variety of life" (Gaston 2000). Explaining the uneven geographical distribution of species assemblages across landscapes is one of the most pressing questions in biology, because global changes are causing a strong erosion of biodiversity (Sala et al. 2000, Parmesan and Yohe 2003). Change in human exploitation, toward more intense soil utilization can largely impact landscape structure and ecosystem functioning (Sala et al. 2000) underpinning many services to society (Costanza et al. 1997, Tilman 1999). In addition, the increase in the use of fossil fuel and the associated emission of CO_2 triggering greenhouse effects (increase of 280 to 370 ppmv since the industrial revolution) has caused the recent fast rise in temperature. Biodiversity is negatively affected by two main anthropogenic pressures on the environment, land-use and climate change (Sala et al. 2000). Those human-induced environmental changes modify species distributions and community compositions at a previously unprecedented rate across the globe (Parmesan and Yohe 2003). While increasing effort is undertaken to monitor the potential decline of species (e.g. Biodiversity Monitoring Switzerland, BDM), our ability to forecast how community will change under increased anthropic pressure remains limited because of the lack of data monitoring trends in biodiversity changes in many places. This severely hinders the development of efficient management options to mitigate the negative effects of global change on biodiversity.

> ***Box 1. Grasshoppers as bioindicators***
>
> Grasshoppers and crickets (Orthoptera) belong to an herbivore insect group. Because of their trophic interactions on a large diversity of plant species, the diversity of grasshopper can reflect the agricultural management of grasslands and therefore constitute a good indicator of habitat quality. Some species are generalist and can be found at almost any meadows while other are highly specialized with strong ecological demands. In addition, grasshopper and cricket show a strong species compositional turnover along elevation gradients with some species dominating lowland habitats, while other restricted to alpine grasslands. Therefore, changes in agricultural management of grasslands and climate change are expected to largely impact orthopteran assemblages. In Switzerland more that 40% of species are already threatened by recent landscape changes. An automated device to monitor the composition of orthoptera in grasslands would constitute a valuable tool for both landscape management practitioners and for scientists aiming at studying species responses to global changes.

Global changes have durable impact on the natural ecosystems. To assure the durability of ecosystem health for future generations, informed management measure should be developed. For this purpose, the acquisition of detailed information on ecosystems in space and time is crucial (Kremen et al. 2007). The accessibility of spatial information on biodiversity in landscape is recommended to have a global management view for designing and assessing conservation actions, and tracking progress in conserving biodiversity. In addition to a good spatial coverage, long-term trends can reveal major shifts in abundance and composition of biological communities within ecosystems. However, the number of temporal versus spatial points usually trade off given the high cost of collecting manually biological data on ecosystem processes. While there is a long tradition of automated measures of the abiotic environment allowing for instance the monitoring of long term change in climate during the last century (e.g. meteorological stations), automated measurements of biotic processes in ecosystems are at a surprisingly very early stage (Aide et al. 2013, Zhang et al. 2013). Increased data availability and quality would allow to produce more robust models of biodiversity such as species distribution models (SDMs) to forecast ecosystem changes under different management scenarios (Pellissier et al. 2013).

Automatized ecosystem of data gathering

Managers are expected to make decisions to mitigate the consequences of global changes on ecosystems. However, decisions are generally based on limited information in term of spatial and temporal coverage. Biodiversity surveys such as the rapid assessments of taxonomic groups at a given place are commonly used to manage landscapes and take conservation decisions. These manual methods requiring the visit by the investigator to sites several times across the year are generally costly and limited in space and time (Sueur et al. 2008). These constraints reduce the researcher's ability to understand the dynamic patterns of ecosystem processes. To improve the efficiency of management decisions, managers need survey techniques that increase the quantity and quality of information available to policy makers. One way to improve the quantity and quality of data in biodiversity surveys is using automated recording systems (ARS) that could potentially collect data continuously at many different sites in the landscape. ARS can continuously monitor ecosystems, every day of the year, in stations across a variety of sites simultaneously, and all recordings can be permanently stored (Aide et al. 2013). Recent development in video or sound monitoring technique has allowed sampling of data on animal behaviour (Aide et al. 2013, Zhang et al. 2013, Stowell and Plumbley 2014). However, ARS development remains at an early stage because research in this technology is still limited.

Box 2. The Swiss orthopteran app

The Swiss orthopteran application (app) makes accessible on mobile phone detailed information on the Swiss orthopteran species. Portraits with detailed information are provided for all 119 orthoptera species in Switzerland and Deutschland, including the combination of different media such as images, sound and video material. Sighted species can be recorded with a "digital notebook" and exported for further processing and sent to a central database such as the Centre de Cartographie de la Faune (CSCF). It is therefore a valuable tool for citizen science and large scale biodiversity sensing. Nevertheless, the implementation of an automated tool for species identification would increase the accessibility of this tool.

Screenshot of the app (Grillus campestris)

Recent technological advances have provided improved methods for the collection of sound data in the landscape in numeric format that can be easily analysed with computer software. Data collected from such equipment can be analysed by means of a visual representation in the form of oscillograms representing plots of amplitude versus time. Oscillograms of orthoptera show species-specific sequences of sound patterns, the chirps, which are formed by sequences of pulses. Across species, the length of songs may vary from under 1 ms in duration to continuous tones lasting minutes, while the frequency content may ranges from below 1 kHz to over 100 kHz (Greenfield 1997). Oscillograms are used traditionally by entomologists as a tool to identify species, in complement to morphology (Baur et al. 2006). Christian Roesti (collaborator of the project) has written a complete compendium of the Swiss orthopteran species including, for each species, the characteristic oscillogram of its song and the onomatopoeic description (Roesti and Keist 2009, Figure 1). The call song of orthoptera contains enough information for species recognition, as its main function is male-female pair-formation and the females of each species succeed identifying the call of males of the same species (Roesti and Keist 2009). As such, this signal could be used for automated species identification in grasslands.

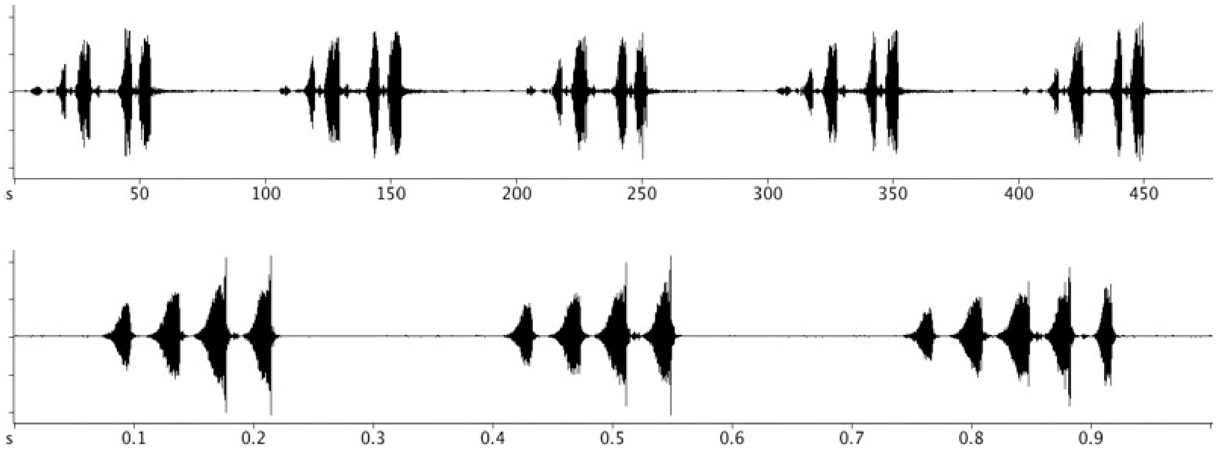
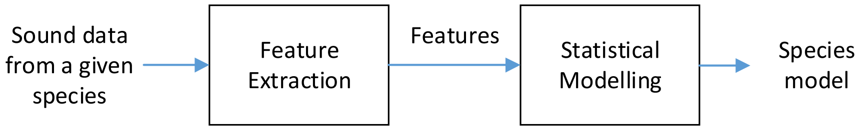


Figure 1. *Oscilliograms of the song of two species of grasshoppers, taken from the database of orthoptera.ch, Decticus verrucivorus and Platycleis albopunctata.*

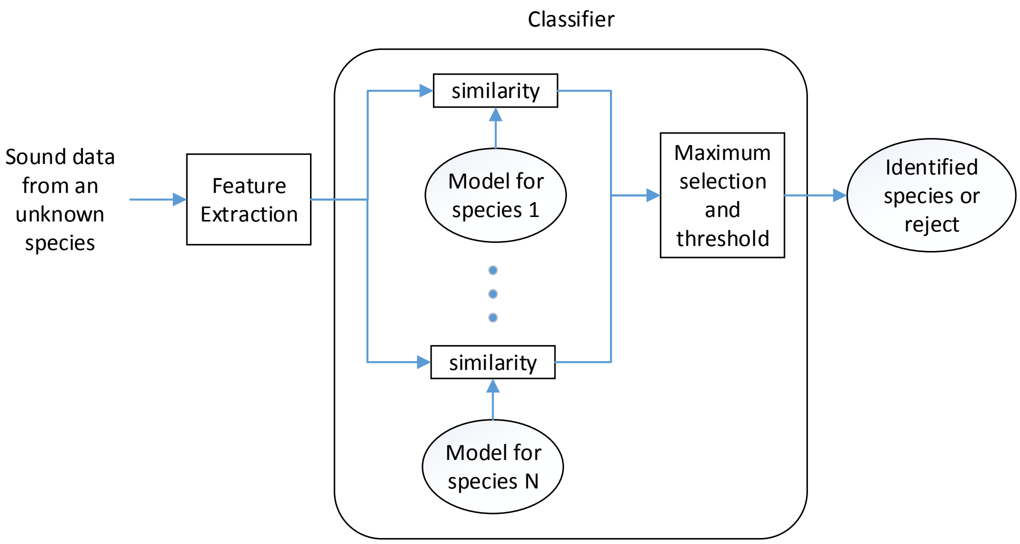
Technically, automated detection of species of orthoptera from sound is feasible but not yet available for deployment (Ganchev and Potamitis 2007, Chaves et al. 2012). Its development to the required level of maturity requires the interdisciplinary research performed by actors working closely and having strong complementary competences in ecology, entomology, sound processing and technological development. Some of the reported temporal and spectral acoustic cues for differentiating among the various species are: (a) The rate and duration of the pulses, (b) The dominant harmonic or pulse carrier frequency, (c) The spreading of the spectral energy (narrow- or wide-band) (d) The intensity and location of tones other that the dominant frequency (Riede 1998, Tauber and Pener 2000, Greenfield 1997, Ganchev and Potamitis 2007). These cues should be captured into signal descriptors, to be presented to a classifier, in order to achieve automatic species detection. Additionally, other high-level features may be exploited such as periodic patterns of pulses and chirps, analogous to the high-level features used in human speaker recognition systems (Kinnunen and Li 2010).

Sound analysis and machine learning for automated identification of insects

The general process for acoustic species identification, shown in Figure 2, consists of two main stages: (a) The extraction of signal descriptors (feature vectors) from the sound signal, accounting for the acoustic cues for species differentiation, (b) The classifier, which compares the input feature vector with a pre-trained statistical mode of each class (species) to be recognised, and choose the class for which the corresponding model is closest to the input. A similar scheme is also used for human speaker and speech recognition (O'Shaughnessy 2000). Therefore, despite differences in sound production mechanisms, speech processing methods can be potentially used for acoustic insect identification including feature extraction based on Mel Frequency Cepstrum Coefficients (MFCC, Davis and Mermelstein 1980) and classifiers based on Gaussian Mixture Models (GMM, Reynolds and Rose 1995), Hidden Markov Models (HMM, Rabiner and Juang 1993) or Probabilistic Neural Networks (PNN, Specht 1990).



(a)Training phase, done for each of the N possible species



(b)Testing phase, done when we have a sound segment to classify

Figure 2. *Block diagram of the analytical steps for the acoustic species identification system*

Several systems have been developed for identification of insects species based on sound (Schwenker et al. 2003, Ganchev and Potamitis 2007, Chesmore and Ohya 2004, Chaves et al. 2012). Ganchev and Potamitis (2007) use Linear Frequency Cepstral Coefficients (LFCC) as features and segment the signal either with fixed-length or variable-length. Using the classifiers Probabilistic Neural Networks (PNN) and Gaussian Mixture Models (GMM), they reached an accuracy of 90% for 307 species. Chesmore and Ohya (2004) extracted features with a purely time domain method, Time Domain Signal Coding (TDSC), coupled with an Artificial Neural Network (ANN) classifier, a standard multilayer perceptron with backpropagation training, and achieved 99 % recognition accuracy on 25 species of British Orthoptera. Chaves et al. (2012) pre-processed the signal to remove periods where no insect call is detected, then extracted MFCC features and used an HMM classifier to achieve recognition higher than 99 % of 26 species. Schwenker et al. (2003) calculated pulse length, pulse distances and pulse (carrier) frequency, to be used as features together with a Radial-Basis-Function (RBF) classifier. The output score of the three classifier is fused and evaluated with a database of cricket songs of 35 different species with a recognition accuracy of 93.7 %. Finally, Zhu and Zhang (2010) used wavelet packet sub-band decomposition converted to cepstrum (SBC) to extract features from insect sounds, and an HMM classifier. The system is evaluated using insect sounds from an agricultural database. Although the work is not applied to orthoptera, we find this technique very promising and will test it in our orthopteran identification system. The frequency intervals of the sub-band decomposition can be adapted to the region of interest of the orthopteran songs and the HMM classifier, with its capability to model temporal sequences, would deal with the time patterns of the songs.

Research of orthopteran acoustic identification is still in its infancy and there is no established practice for selecting the appropriate features or classifier (Ganchev and Potamitis 2007, Chaves et al. 2012). In this project we will make a step forward by using sufficient data, collected purposely for the needs of the research targeted to produce an automated system to monitor orthoptera at a given site and use this information for ecosystem management. We will study and develop feature extraction adapted to the recognition of the species of interest and implement it as a publicly available smartphone application. This project bridging ecology and signal processing could only be achieved in the frame of such a SNF interdisciplinary research, by combining our complementary knowledge on biodiversity monitoring, orthoptera song characteristic and recording, sound analysis and recognition, on technological development, and on spatial species distribution modelling.

2.2 Own research

Prof. Loïc Pellissier (ETHZ/WSL):

LP research domain is the ecoinformatic with a strong orientation **toward monitoring species distribution in the landscape and modelling responses to global changes**. Overall LP research has involved the development of novel modelling approaches to forecast species range shift under climate change (Pellissier et al. 2015), understanding climate-biodiversity relationships (Pellissier et al. 2012, 2014), plant-herbivore interactions along environmental gradients (Rasmann et al. 2014), and community assembly processes (Pellissier et al. 2013, LeRoux et al. 2014). In his dissertation, he proposed novel techniques to model species assemblages in space and time (Pellissier et al. 2013). LP post-doctoral time at the University of Aarhus in Denmark was financed by the Danish Research Council to study the effect of climate change on the Arctic fauna and flora (LeRoux, et al. 2014, Pellissier et al. 2015) by monitoring of species and abiotic features of the landscape. At the end of 2013, LP was hired as lecturer and junior group leader at the University of Fribourg with funding to initiate a new research project. This project involves a PhD student and focuses on the impact of the rapid colonization of insect herbivores on alpine plant composition under climate change. High elevation plants experiencing lower levels of herbivory have evolved relaxed defence syndromes compared to their low-land living relatives. With increasing temperature under on-going climate change, increased herbivore abundance, especially orthoptera, is expected to strongly impact alpine vegetation. LP research in forecasting species and ecosystem responses to climate change in the landscape requires new monitoring tools that will be developed in the context of this interdisciplinary project.

LP is currently assistant professor at ETH Zurich and WSL Birmensdorf and pursuing his research on species response to global changes. Overall, LP has an excellent publication record in high-impact journal such as a first author publication in *Science*, three publications in *Nature Climate Change* (one as senior author), two in *Ecology Letters* and the top journals in his field including *Ecology*, *Global Ecology and Biogeography*, *Molecular Ecology*, *Journal of Biogeography*, *Diversity and Distribution* and others. His work has resulted in 68 publications in peer reviewed ISI-listed journals and a further 3 papers in non-ISI journals or books (total 71 publications cited >1300 time in Google Scholar since 2010, H=17).

Prof. Pierre-André Farine (EPFL/ESPLAB):

PA Farine is a Full Professor at EPFL and Head of the Electronics and Signal Processing Laboratory (ESPLAB, http://esplab.epfl.ch) which has over 30 collaborators and has been working for more than 15 years in the fields of **low-power integrated circuits and systems, including wireless and wired communications, global and local positioning, sensor networks, instrumentation, and bioengineering**. This research have given rise to several publications in peer-reviewed conferences and journals (http://infoscience.epfl.ch/curator/export/8730/). His laboratory has strong expertise in signal processing algorithm design, optimization and implementation in low-power portable devices, complying with real-time and low-power consumption and for different applications domains including image and audio compression and recognition. The list of recent projects is at http://esplab.epfl.ch/page-115052-en.html. Examples of current projects involving signal processing and pattern recognition are: CTI-3DCR (Three Dimensional Coin Recognition), CTI-MINOS (MEMS Inertial Motion Sensing watch for sport and wellness), and CTI-IOP24 (Eye sensor contact lenses and portable device for continuous Intra-Ocular Pressure measurements).

Dr. Sara Grassi (co-requérant at EPFL/ESPLAB):

Sara Grassi is a scientist and Team Leader at ESPLAB. Her research is in algorithm development and implementation for portable devices, particularly **speech and image processing compression and recognition**. Currently she is leading the project CTI-MINOS, in collaboration with the Swiss watchmaker industry: the signals of 3D accelerometer and pressure sensors are analysed to recognise periods of locomotion and to derive a precise measure of steps, travelled distance and velocity. The algorithm is implemented in a primary-cell powered wristwatch. She is also working on the mandate "MESACO" for Swiss watchmaker industry: the acoustic signal a mechanical watches is analysed to measure the rate deviation and the amplitude of the movement. Previously she has worked in designing and implementing image recognition under project CTI-Pictobar (Ayyalasomayajula, Grassi and Farine 2011) and co-directed the PhD thesis "Low Complexity Image Recognition Algorithms for Handheld Devices". She has also worked on the project CTI-Attrawatch, implementing speech compression and recognition in a wristwatch (Grassi et al. 2008), in analysis of EEG Brain signals to infer human movement intentions (Jorquera, Grassi et al. 2013), in speech recognition for C&C interface in low power device (Grassi et al. 2003), in techniques for wideband speech compression (Biundo, Grassi et al. 2002) and in speaker recognition over compressed speech (Grassi et al. 2000). She holds a PhD from University of Neuchâtel, thesis on “Optimized Implementation of Speech Processing Algorithms”, a Master in "Communications and Signal Processing" from Imperial College, London, and Electronics Engineer degree from USB, Caracas.

2.3 Detailed research plan

2.3.1 Aims of the study

Automated Recording Systems (ARS) applied to continuous recording and detection of a group of species that are good bioindicators of ecosystem health and change would represent an advance for landscape monitoring and modelling of ecosystem responses to global changes. In this project, we will develop a method to monitor automatically orthoptera composition at a given site and use this information to map species distribution and model species responses to climate change. The first main objective is technical and involves the development of an algorithm to correctly identity orthoptera species from features extracted from their songs. The second objective is to test the ability of the species identification algorithm to correctly identify several co-occurring and co-singing species at a given site, as a tool for long-term monitoring. The third objective is to implement the algorithm in an existing smartphone application (the Swiss orthoptera app) as a tool to promote citizen science which might allow a large scale biodiversity data collection across Switzerland, together with knowledge transfer to the public.

Part 1: Developing the sound recognition algorithm

The first part of the project aims at developing a sound recognition algorithm to identify the orthoptera species occurring in Switzerland. In particular, we aim at answering the following questions:

1. Can we automatically distinguish species from their song signals?
2. What are the most relevant features to extract from the sound signals in order to distinguish species from each other and which classifier technique performs the best?
3. How to account for the effect of temperature, and other environmental conditions, on the sound signal emitted by a given species?

Part 2: Study of sound from species assemblages

The second part of the project aims at testing the automated recognition algorithm as a monitoring tool of orthoptera assemblage in space and time. We will use a commercially existing sound recording platform (http://www.wildlifeacoustics.com/) with good data storage abilities and low battery demand. This platform will be deployed in 20-30 grasslands along elevation gradients together with visual field sampling, a strong skill in the Landscape Ecology group at ETHZ. The very detailed information on orthoptera behaviour will be used to better understand species distribution along environmental gradients. This second part of the project aims at answering the following questions:

1. Can the algorithm identify the individual sound of a given species from the concert of sound from multiple individuals and species?
2. Does the predicted species composition from the sound match the observed composition, both temporally (following phenology) and spatially (along elevation gradients)?
3. Does phenology drives species distribution along elevation gradients?

Part 3: Implementation of the app, data gathering and modelling

In the third part of the project, we address the possibility of implementing the algorithm within a smartphone application. Data from the smartphone can be transferred to a server with species identifications, quality score and GPS coordinates that can feed into a database. In turn, such data acquisition will allow to refine the species distribution model of species across Switzerland and the projected responses to climate change.

1. Is the sound recorded by the most recent generation of smartphone of sufficient quality to identify orthoptera?
2. How to optimize the application to be able to run it on a smartphone system?
3. Does data gathering from the users of the app improve knowledge on species distribution, the quality of species distribution models and realistic forecasts under climate change?

2.3.2 Methods

Existing sound database

The first part of the project relies on an existing sound database collected for all species in Switzerland under different temperature conditions and in different biogeographic regions. This database contains **more than 2000 records performed by Christian Roesti (collaborator of the project) on 106 orthopteran species** in the different regions of Switzerland (www.orthoptera.ch). This existing sound database will provide the raw material for a fast assessment of the best features and classifiers to identify automatically orthoptera species from their songs.

Algorithm for acoustic orthopteran identification

The core of the project consists on developing an algorithm for accurate and robust automatic identification of Swiss orthopteran species on continuous acoustic field-recordings. The algorithm consists of two stages. The extraction of signal descriptors (features) and the classifier. From the previously used techniques presented in introduction, we plan to investigate the following:

1. Feature Extraction
   1.1. Pre-processing: offset removal, pre-emphasis, amplitude normalisation.
   1.2. Segmentation: fixed-length and-variable length, the latter using an end-point detector based on energy, either of the full signal or of specific frequency bands combined with other features such as zero-crossing.

1.3. Signal descriptors: Spectral and temporal features such as LFCC, SBC, dominant frequency, pulse rate and duration, TDSC.
1.4. Post processing: cepstral mean subtraction and feature normalisation.

2. Classification:
   2.1. Classifier types: GMM, PNN, HMM.
   2.2. Classification scheme: straight, semi-straight and fully hierarchic
   2.3. Fusion of classifiers: Averaging and voting

Additionally we will investigate the use of feature reduction techniques such as PCA and LDA to condense the signal descriptors into a lower dimensional vector. We will also consider additional descriptors, such as (1) Temporal: energy, zero-crossing, percentiles, moments (mean, variance, skewness, kurtosis), (2) Spectral: centroid, flatness, spread, flux, inharmonicity, moments. If necessary we will also explore other classifier techniques such as template-matching techniques (dynamic time warping DTW), Logistic Regression, Support Vector Machines (SVM), and decision trees (Alpaydin 2014, James et al. 2014). The algorithms will be programmed under Matlab language (http://www.mathworks.com/) to benefit from comprehensive signal processing and machine learning libraries and third party software from research groups. We will also use HTK (http://htk.eng.cam.ac.uk/), a set of library modules and tools available in C language, covering speech analysis and HMM training, testing and results analysis as well as openSMILE feature extraction tool (http://www.audeering.com/research/opensmile) written in C++ which calculates and combine a vast amount of features used in Music Information Retrieval and Speech Processing.

Controlled room and community field sampling

In order to validate the ability of the algorithm to distinguish species within a community, we will collect community sound data in both controlled laboratory conditions and from natural sites. First, we will record sound in a controlled laboratory room, where there is no background noise. We will capture species in the field, identify them and place them in a laboratory chamber with food. We will record the orthoptera sound for a long duration to increase the chance of non-overlapping songs from different species. In addition, the room temperature during the recordings will be manipulated and documented with thermologgers to assess the ability of the algorithm to detect species under distinct temperature conditions.

Second, we will select grassland patches using a random stratified sampling (Pellissier et al. 2010, Pellissier et al. 2013) along elevation gradients in four main biogeographic regions of Switzerland (Ticino, Valais, Graubunden and Prealpes). The PhD student and the entomologist will inventory the orthoptera species present on surfaces of 30 by 30 meters. To ensure a complete sampling and to have an indication about the phenology, those sites will be sampled three times across the season. The “Song Meter SM3” (http://www.wildlifeacoustics.com/products/song-meter-sm3) sound monitoring platform installed to target sound from the ground will be installed in the centre of the square. This device has low power demand (around .05 mW) and sufficient data storage to record up to 260 hours. The SM3 can remain idle for months and desired recording schedule can be set up. We expect to sample around

20-30 sites, 5-8 in each elevation transect, depending on meteorological conditions and other field logistic constrains. In each of those sites we will collect the sound automatically daily during 1.5 hour during the early afternoon. Local variables will be collected including habitat types or surrounding agriculture types. Temperatures will be measured hourly using thermologgers.

Analytical steps

We will go through the following series of analytical steps to answer the main research questions on developing the algorithm for species identification and the potential use for scientific monitoring and citizen science data gathering.

Subproject 1: Developing the sound recognition algorithm

1.1 – We will build a baseline recognition system using standard spectral features (SBC or LFCC) and GMM classifier and investigate their performance. We will find the best set of features having large variation across species, and small variation across individual of the same species and across unwanted factors (e.g. noise and environmental sounds, variation in recording conditions). This is most critical to achieve high accuracy and robustness. We will systematically investigate features used in previous work on insect recognition as well as many other encountered in different application domains of classification. These features will be investigated with both statistical tests to assess their significance and by combining them with a classifier and using feature selection methods such as forward/backward and genetic algorithm (Alpaydin 2014, James et al. 2014). Once the best features chosen, we will investigate different classifiers, with several iterations between the feature choice and the classifier choice and dimensioning. We will use the existing database of sound of orthopterans species in Switzerland, dividing the data into three sets (training, evaluation and test) and use only the first two and cross-validation for developing the algorithm and the third for final testing. We will retain algorithms whose complexity seems suitable for the foreseen smartphone application. Retained algorithms will be coded in C using fixed-point arithmetic and tested to assess performance and complexity, as this will be needed later for the integration into the smartphone application (Kehtarnavaz et al. 2015). The postdoc at EPFL will lead the development of the algorithm together with the help of the orthoptera experts.

1.2 – The postdoc researcher at EPFL will in addition investigate a way to account for the variation of the emitted song across temperature for a given species. Orthopterans are thermal conformers and many studies report that their songs vary according to ambient temperature (Greenfield 1997). Pulse rate changes in response to temperature whereas frequency does not show a significant variation across temperature. Observations suggests that variations may be species-specific and that there is a lower temperature limit for stridulation (e.g. 15-17 °c for *Ephippiger ephippiger*) then a range of temperature (e.g. 19-27 °c) in which the pulse rate increases almost linearly with temperature and a temperature above which the pulse rate does not vary anymore with increased temperature. For a reduced set of species of interest, we will study and model the effect of temperature on their song, using sound recordings of the same species at different temperature in both controlled and field conditions. Then we will study different compensation strategies at different levels of the system (features, species models, fusion of classifiers). We will also investigate the use of features that do not change significantly with temperature, as suggested in Ganchev and Potamitis (2007), when they use the dominant harmonic and frequencies (LFCC) and pulse duration, but do not use the time lag between subsequent pulses because it varies across temperature. Finally, we will also investigate the approach in which the temperature is included as a feature in the classification, either by directly appending it to the feature vector for training and testing, or by using it, e.g. to select among subsets of classifiers, each trained with data corresponding to a range of temperatures.

Subproject 2. Study of community sounds

2.1 – Using the recordings of species assemblages in controlled experimental chamber, we will develop an approach to distinguish individual sound from the concert of sound from multiple individuals in a community. The community sound monitoring data will have long recordings, increasing the chance of containing songs from more than one orthopteran from the same or different species, potentially singing together. Gathering the classification statistics by calculating over a long audio sequences increases thus the chance of getting ambiguous classification results. The classification must be done continuously on shorter, meaningful, intervals, based on the appropriate energy level. We will thus design a detector of the events of interest and separate them from background noise, by moving a sliding window across the raw data, calculating the spectrum of the signal inside the window, calculating maximum energies and combining them to be used as the detector confidence. Once the intervals of interest are found, we will extract the features of each interval for species recognition, and input them to each of the species model of the classifier, obtaining the probability of presence of each of the species in a given time interval. This analytical part will be conducted jointly by the postdoc at EPFL together with the PhD student, who will help set up the orthoptera recording in the controlled chambers.

2.2 –The PhD student together with the entomologist will sample 20-30 grasslands across Switzerland. The PhD student will deploy the “Song Meter SM3” in the field at 20-30 sites. At the end of the field season, the PhD student will recover the recordings collected in the sites along elevation gradients and apply the post-processing species recognition algorithm. We will compare the predicted species composition from song call recognition from the species list established by the entomologist through visual sampling. The entomologist skilled at identifying species from songs will also listen to specific sections of the audio band and produce an expert-based species list from the recordings. We will compare the species composition detected using the algorithm to the observed composition (in the field, and expert-based audio identification) by computing the percent of correctly predicted presences and absences for each site together with metrics such as the Area Under the Curve or the True Skill Statistic (Allouche et al. 2006). In addition, we will compute metrics representing structure of the communities (e.g. richness) and compare observed to predicted richness along elevation gradients to assess whether the algorithm performs better in some part of the elevation gradient (e.g. poorer sites) or regions (e.g. due to too much song similarity across species).

2.3 – The algorithm applied to the entire records for a full year across the 20-30 sites will provide information unavailable so far combining species distribution along gradients together with phenological data. With continuous data of species activity that matches daily recorded temperature data, the behaviour, phenology and physiological limit of species will be much better understood. Spatio-temporal data on species activity will inform on how phenology can explain species distribution along environmental gradients (Chuine et al. 2010). The PhD student will extract from the recordings the first and last singing date for each species. The first singing date combined with hourly thermologgers records will provide a measure of how much energy (expressed in degree-days) is required to reach sexually active adulthood and the relationship will be compared among sites. Using species distribution models, we will relate statistically species distribution along elevation gradients to degree-days computed from thermologgers and other environmental variables including moistures, and vegetation descriptors (Pellissier et al. 2013). It is expected that species-specific environmental thresholds discriminating presence and absence along elevation gradients relate to phenological traits as a proxy of development time (Kocher, Pellissier et al. 2014). This increased ecological understanding of species phenological response to available energy will improve species distribution model forecasts under climate change (Chuine et al. 2010).

Subproject 3. Implementation of the app, data gathering and modelling

3.1 – We will use the sound of species recorded by the most recent generation of smartphones and test how the algorithm perform on these lower quality sound records. Two issues may arise: (1) the sound of interest is too low due to not enough pre-amplification, sensitivity and directionality of the built-in microphone. (2) The loss of recognition accuracy due to the mismatch between training and testing conditions. The user must make sure that the sound recorded is at a reasonable level (close enough to the source) and that the audio settings are appropriate. Some form of Adaptive-Gain-Control (AGC) may be included in the app in order to set the analogue input volume at an appropriate level as well as display aid to the user to help him find the good settings. Pre-emphasis and filtering, as well as the use of robust features may also help in mitigating this problem, but there are limits to the benefits of this techniques, and the use of an external microphone should also be considered, with the added advantage that it will overcome the variability among microphones of different smartphones. The mismatch between the recording conditions of the (training/evaluation/testing) data used for developing the system and the recording conditions of the sound being recognized at deployment would result in accuracy degradations that are known to reach 30-40 % when this situation occur in fields such as speaker/speech recognition (Murthy et al. 1999). This problem has been investigated in these fields during decades and there is a variety of solutions we may borrow from, such as cepstral mean subtraction (CMS), the choice of features robust to mismatch, and different forms of adaptations of the classifier models (Rabiner and Juang 1993, Murthy et al. 1999). The assessment of the transferability to smartphone will be conducted by the postdoc at EPFL.

3.2 – We will implement the algorithm within the application to be able to run it on a smartphone. The smartphone application will allow to make recording of 20-30 seconds that will be processed for recognition. The application may also ask the user for information about the ambient temperature together with information on the habitat and biogeographic region to increase the accuracy. This information together with the GPS coordinates measured by the device is used to look-up stored information on which species could be present and restrict the classification (based on main biogeographic regions) to search only the models of those species. For both Android and iPhone smartphones there is support for the execution of signal processing C-code (Kehtarnavaz et al. 2015). Usually the processor of these devices is based on ARM architecture. Once the recognition algorithm developed under Matlab, we will translate it into C language, assess the complexity and simplify it if needed, and if possible by trading-off performance. To further reduce complexity some algorithm blocks could be rewritten using fixed-point arithmetic optimized for target ARM processor. The C-coded algorithm will then be integrated into the smartphone app by the software engineer in interaction with the ZHAW institute. We will integrate in the app the connection to a central server located at ETHZ to upload information and update the local information (species and background models, species geolocation information, etc.). Once a species is detected the application will ask the user to send the data to the server or store it for sending later when the smartphone is connected via WIFI. In this case there may also be the option to send the audio file along, to allow further improvements on the classifier, such as updating the models of the species and of the background noise and other environmental sounds encountered, as well as carry out a more complex, but more accurate classification on the server. The institute for Applied Simulation (IAS) from the ZHAW in interaction with an engineer office (http://www.garzotto.ch/gmbh/) has a strong experience with app programming and has developed the orthoptera app. They will guide the work of the software engineer.

3.3 – We will provide the app for download to 1000 selected users of the application across Switzerland to beta test it in their respective regions. The PhD student will assess whether the application allows better mapping and modelling of the distribution of the species across Switzerland. To demonstrate the interest of biodiversity data gathering by citizen, we will plot for each region, the mean species number through time in each 5x5 km cell. This will inform on how much knowledge is added by the app through time. Then, we will assess how this knowledge improves the models of species distribution. We will apply species distribution model based on the existing database of orthoptera occurrences of the Swiss Center for Faunal Cartography (CSCF) and then build updated models monthly based on the new collected occurrences. We will evaluate the model improvement through time as the information accumulates. Based on meteorological station and thermologgers data, we will compute several climatic variables including degree-days and minimum temperature, and NDVI, a remote sensing layer representing the vegetation. We will use several species distribution modelling techniques including generalised linear models (GLMs), generalised additive models (GAMs), and gradient boosting machines (GBMs) computed using the biomod2 R package with parameters optimized for species distribution modelling (Thuiller et al. 2009). We will validate the model predictive power on the 20-30 sites collected across Switzerland during the second part of the project. Finally, once the model accuracy is satisfactory, species response to climate change will be forecasted. As current climatic conditions, we will use the average of the 1981-2009 periods that corresponds to the new reference period used by the Center for Climate System Modelling (http://www.c2sm.ethz.ch/). The resulting current and future distribution maps, will be made available on the website www.orthoptera.ch and on the orthoptera app.

2.4 *Project organisation, schedule and milestones*

Here, we describe how each project section will contribute to develop the species detection system and use this information for research activities. P1: The main data to develop the first part of the project is provided by Christian Roesti, the entomologist collaborator of the project. The EPFL/ESPLAB will take advantage of this database to develop the speech recognition algorithm, thanks to their strong signal processing experience. P2: The second part of the project uses the skills in engineering at EPFL. Its deployment and use of spatially replicated information will benefit from the strong skills in sampling design and modelling in the Landscape Ecology group at ETHZ. In addition, the novel data spatio-temporal collected will be used to better understand species distribution and responses to climate change. P3: The implementation of the algorithm developed at EPFL in the orthoptera app will be done in strong collaboration with the ZHAW, who developed the Swiss orthoptera app. The project is planned for one PhD student during 3 years at ETHZ, a postdoc during two years at EPFL, a field entomologist during three months and a computer engineer during 6 months. Prof. Pellissier and Prof. Farine will take the project lead and assume an active role in all analyses and discussions. The postdoc at EPFL will develop the species recognition algorithm from the sound database and translate it to C library. He will also help in developing the platform for sound recording to be deployed in the field. The PhD student will set up the laboratory grasshopper manipulation of composition, and deploy the platform on the sites across Switzerland. He will evaluate the performance of the algorithm on those assemblages and use the data for ecological studies and in particular species distribution modelling. The field entomologist will conduct the visual sampling of the orthoptera on the sites. Bachelor and Master students are expected to assist during the field campaign. Finally, the software engineer will implement the algorithm in the Swiss orthoptera app. The detailed schedule of the tasks for the 3 years is given below.

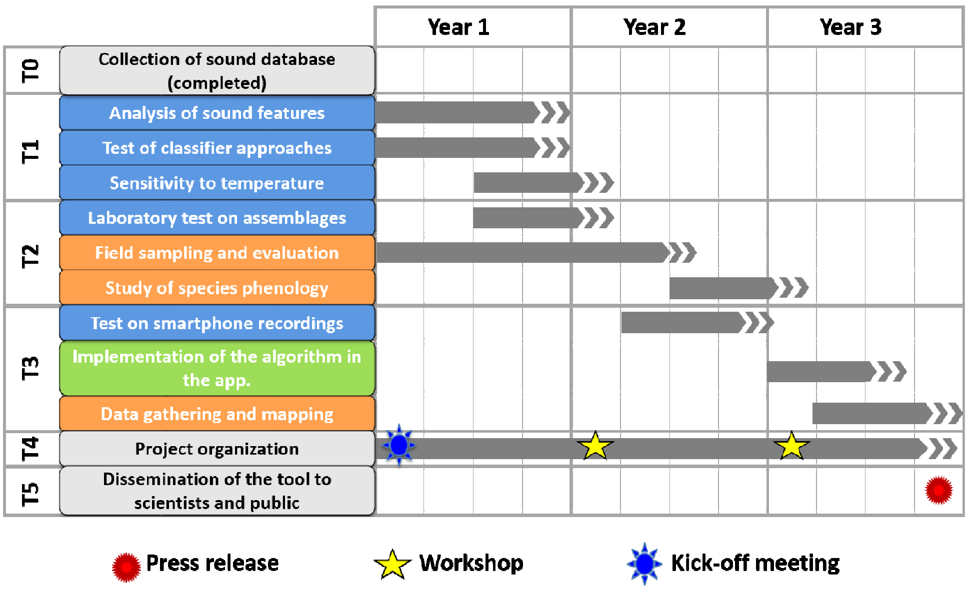


Figure 5. *Time table of the different tasks of the project. The colour code represent the different actors (blue=postdoc at EPFL, orange=PhD at ETHZ and green=software engineer).* <u>*Months 1 to 9*</u>*: During the first phase of the project the Postdoc researcher at EPFL will use the sound database to identify the best features and classifiers to discriminate the species (T1.1 and T1.2). During the same period, the*

PhD student will prepare and lead the fieldwork deploying the devices to record community sound data in the 20-30 sites together with some recording using smartphones (T2.2). He will also provide insect individuals for the laboratory trials of species assemblage detections (T2.1). <u>Months 9 to 18</u>: As soon as the sites have been inventoried, the PhD student with the help of the Postdoc will evaluate the algorithm on real assemblages collected in the field (T2.2). <u>Months 18 to 24</u>: the PhD student will analyse the phenological data collected in the field (T2.3). The Postdoc will make trials with the sound recorded from smartphones and optimize the algorithm (T3.1). <u>Months 25 to 30</u>: The software engineer will implement the algorithm in the application and the application to gather the data on the server (T3.2). <u>Months 21 to 36</u>: The PhD student will distribute the application to 1000 beta testers including amateurs and schools, and analyse the data acquisition and model performance. The project organisation will involve two workshops with the project collaborators (T4) and publicize largely the application (T5).

The milestones for the coordination of the project include:

(1) An initial workshop (kick-off meeting) at one location with all project participants. This will include 2 days of in-door sessions in which the technical aspects of the project will be fully discussed. After the recording setup has been developed, we will together establish a first pilot deployment at one site. This joint field work will put the sampling methods to a test of practicability, allow for necessary modifications, and will ensure that the approach is both practical in the field and provide good quality information for species identification. (2) Quarterly meetings of the PI of the project together with the PhDs and Postdocs at rotating locations (Microcity, ETHZ) for administrative aspects and for fine-tuning research activities. (3) Annual reports to SNF after the annual meeting with collaborators. (4) A final symposium organized on the subject of biodiversity monitoring to highlight the new developed tool. This will involve all project participants plus interested researchers and environmental managers in Switzerland. Our shared goal will be to stimulate a new generation of scientists to better apply new technological development to find solutions for biodiversity erosion across the globe, making use of exciting new technologies currently emerging.

2.5 Importance and impact

The proposed work addresses the long-standing problem of data acquisition for conservation efforts around the globe which is one of the reasons for the difficulty to gather spatio-temporal data across entire landscapes. The strength of our project is to combine together the relevant fields of research to develop such a new tool for biodiversity monitoring. The project will educate a PhD student and a Postdoc and is certain to attract additional Master students whose projects can be linked to the proposed research. Project results will be published in the leading subject and the highest impact journals, and press releases will also help raising public awareness for biodiversity issues. In addition, by gathering more complete data on species distribution and phenology across environmental gradients, we will gain an understanding of the factors that shape biodiversity at a landscape scale. More specifically, this project will contribute significantly to: (i) a novel approach to record biodiversity across the landscape for long time periods, (ii) the development of an application for citizen science and collecting data across the landscape, and (iii) increased cost efficient method for monitoring species responses to global changes. The project will interest the public in general given the publicly available smartphone application. We expect that our application might become a major tool for large scale evaluation and monitoring of biodiversity. For instance, biological agriculture is largely developing in Switzerland and farmers are interested to estimate in the impact of their effort and promote the biodiversity enhancement. Our project would provide an easy tool for such quantification. Finally, this technology will allow for the establishment of a low-cost continuous monitoring network of how biodiversity is responding to climate across Switzerland.

3. Interdisciplinary research

The project is integrated to conduct trans-disciplinary research at the frontier between electronic/signal processing and environmental science. The proposed project is not feasible in an individual project and requires to take advantage of the complementary strengths of the participating groups. Monitoring and modelling how biodiversity is changing in the landscape require novel tools that can be developed only through the interdisciplinary collaboration between researchers having strong complementary competences in the required fields: the entomologist with his excellent knowledge of orthopteran species and the sound they produce, the EPFL-ESPLAB know-how in electronics and signal processing necessary to develop the algorithm for species recognition and implement it in a portable device, the landscape ecologists at ETHZ/WSL that will incorporate this technology into species monitoring and the app programmer to make this tool available to the public. We argue that such approach is the only way to clearly promote a widespread acquisition of data to meet the challenge of conserving biodiversity under global changes. The development of our research agenda has been a conversation with strong mutual interest from the start, with input from project collaborators in particular from the entomologist with an excellent knowledge of orthoptera. The integration of the project is centred around (1) developing a working algorithm for species recognition, (2) application to monitor assemblages in the field to provide more knowledge on the ecology of those organisms, and (3) sharing this tool to increase citizen awareness to the problem of biodiversity erosion and involve them in the solution, whose first step is an evaluation of the extant distribution of species in Switzerland. We are eager to perform such interdisciplinary work together and we anticipate that our project will lead to productive research. EPFL-ESPLAB will apply and extend its knowledge in sound processing and algorithm implementation into the new domain of insect recognition. In parallel, ETHZ/WSL will greatly enhance its research in landscape monitoring and climate change effect, by having the possibility of automatically monitoring species composition continuously in space and time instead of the limited possibilities offered nowadays by the manual field sampling. In turn, this project will educate one postdoc in the field of signal processing at EPFL, and one PhD student who will be versed in using new technological development in signal processing to solve pressing questions in ecology and species responses to global changes.

4. References

Allouche, O., Tsoar, A., & Kadmon, R. (2006). Assessing the accuracy of species distribution models: prevalence, kappa and the true skill statistic (TSS). *Journal of applied ecology*, 43, 1223-1232

Ayyalasomayajula P., Grassi S. and Farine P.-A. (2011) Low complexity image recognition algorithm for handheld applications, Proc. of the 7th Conference on Ph.D. Research in Microelectronics and Electronics, PRIME, pp. 165-168. IEEE.

San Martin Jorquera F., Grassi S., Farine P.-A. , Contreras-Vidal J. L. (2013) Classification of stance and swing gait states during treadmill walking from non-invasive scalp electroencephalographic (EEG) signals", In: Pons JL, Torricelli D, Pajaro M, editor. Converging clinical and engineering research on neurorehabilitation. Berlin: Springer. 2013 Springer, p. 507-511.

Grassi S., Ansorge M., Pellandini F., Farine P.-A. (2003) Implementation of Automatic Speech Recognition for Low-Power Miniaturized Devices", Proc. of 5th COST 276 Workshop on Information and Knowledge Management for Integrated Media Communication, Prague, Czech Republic, pp. 59-64.

Biundo G., Grassi S., Ansorge M., Pellandini F., Farine P.-A. (2002) Design Techniques for Spectral Quantization in Wideband Speech Coding", , Proc. of 3rd COST 276 Workshop on Information and Knowledge Management for Integrated Media Communication, Budapest, Hungary, pp. 114-119.

Grassi S., Besacier L., Dufaux A., Ansorge M., Pellandini F. (2000) Influence of GSM Speech Coding on the Performance of Text-Independent Speaker Recognition, Proc. of EUSIPCO 2000, European Signal Processing Conference 2000, Tampere, Finland, pp. 437-440.

Aide, T. M., Corrada-Bravo, C., Campos-Cerqueira, M., Milan, C., Vega, G., and Alvarez, R. (2013). Real-time bioacoustics monitoring and automated species identification. *PeerJ*, 1, e103.

Alpaydin E. (2014) Introduction to machine learning, 3rd ed., The MIT Press.

Baur B., Baur H., Roesti C., Roesti D. (2006) Sauterelles, Grillons et Criquets de Suisse. Haupt Verlag.

Chaves, V. A. E., Travieso, C. M., Camacho, A., & Alonso, J. B. (2012). Katydids acoustic classification on verification approach based on MFCC and HMM. Proceedings of the 16th IEEE International Conference on Intelligent Engineering Systems (INES), 561–566.

Chapin III, F. S. et al. (2000). Consequences of changing biodiversity. *Nature*, 405, 234-242.

Chesmore, E. D., and Ohya, E. (2004). Automated identification of field-recorded songs of four British grasshoppers using bioacoustic signal recognition. *Bulletin of Entomological Research*, 94, 319–330.

Chuine, I. (2010). Why does phenology drive species distribution? *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 365, 3149-3160.

Costanza, R. et al. (1997). The value of the world's ecosystem services and natural capital. *Nature*, 387, 253-260.

Davis, S. Mermelstein, P. (1980) Comparison of Parametric Representations for Monosyllabic Word Recognition in Continuously Spoken Sentences. In IEEE Transactions on Acoustics, Speech, and Signal Processing, Vol. 28 No. 4, pp. 357-366.

Ding, Y. D. J. G., Griggs, D. J., Noguer, M, van der Linden, P.J., Dai, X, Maskell, K., and Johnson, C. A. (2001) *Climate change: the scientific basis*. Vol. 881. Cambridge: Cambridge University Press.

Espíndola, A., Pellissier, L., Maiorano, L., Hordijk, W., Guisan, A. and Alvarez, N. (2012), Predicting present and future intra-specific genetic structure through niche hindcasting across 24 millennia. *Ecology Letters*, 15, 649-657

Foley, J. A. et al. (2005). Global consequences of land use. *Science*, 309, 570-574.

Gaston, K. J. (1996). Species-range-size distributions: patterns, mechanisms and implications. *Trends in Ecology & Evolution*, 11, 197-201.

Ganchev T. and I. Potamitis (2007) Automatic acoustic identification of singing insects, *Bioacoustics* 16, 281-328.

Greenfield, M. D. (1997) Acoustic communication in Orthoptera, In The Bionomics of Grasshoppers, Katydids and their Kin (ed. S. K. Gangwere, M. C. Muralirangan and M. Muralirangan), pp.197–230. Wallingford, UK: CAB International.

James G., Witten D., Hastie T., Tibshirani R. (2014) An Introduction to Statistical Learning with Applications in R, Springer-Verlag New York.

Kinnunen T. and Li, H. (2010) An Overview of Text-Independent Speaker Recognition: from Features to Supervectors. *Speech Communication*. Volume 52, 12–40.

Kehtarnavaz, N., Parris, S., Sehgal, A. (2015) Smartphone-Based Real-Time Digital Signal Processing. *Synthesis Lectures on Signal Processing*, 7, 1-157.

Kocher, S. D., Pellissier, L., Veller, C., Purcell, J., Nowak, M. A., Chapuisat, M., Pierce, N. E. (2014). Transitions in social complexity along elevational gradients reveal a combined impact of season length and development time on social evolution. *Proceedings of the Royal Society of London B: Biological Sciences*, 281, 20140627.

Kremen, Claire, et al. (2007). Pollination and other ecosystem services produced by mobile organisms: a conceptual framework for the effects of land-use change. *Ecology Letters*, 10, 299-314.

Le-Qing, Z., Zhang Z. (2010). Insect Sound Recognition Based on SBC and HMM. International Conference on Intelligent Computation Technology and Automation (ICICTA), 2, 544-548, 11-12.

Le-Qing, Z. (2011) Insect Sound Recognition Based on MFCC and PNN. *International Conference on Multimedia and Signal Processing (CMSP)*, 2, 42-46.

le Roux, P. C., Lenoir, J., Pellissier, L., Wisz, M. S., and Luoto, M. (2013). Horizontal, but not vertical, biotic interactions affect fine-scale plant distribution patterns in a low-energy system. *Ecology*, 94, 671-682.

Murthy H., Beaufays F., Heck L., Weintraub M. (1999) Robust Text-independent Speaker Identification over Telephone Channels, IEEE Trans. on Speech and Audio Processing, 554-568.

O'Shaughnessy, D. (2000) Speech Communications: Human and Machine, Wiley-IEEE Press, New York.

Parmesan, C., & Yohe, G. (2003). A globally coherent fingerprint of climate change impacts across natural systems. *Nature*, 421, 37-42.

Pellissier, L., Ndiribe, C., Dubuis, A., Pradervand, J. N., Salamin, N., Guisan, A., and Rasmann, S. (2013). Turnover of plant lineages shapes herbivore phylogenetic beta diversity along ecological gradients. *Ecology letters*, 16, 600–608.

Pellissier, L., Alvarez, N., Espíndola, A., Pottier, J., Dubuis, A., Pradervand, J. N., and Guisan, A. (2012). Phylogenetic alpha and beta diversities of butterfly communities correlate with climate in the western Swiss Alps. *Ecography*, 36, 541–550

Pellissier, L., Fiedler, K., Ndribe, C., Dubuis, A., Pradervand, J. N., Guisan, A., and Rasmann, S. (2012). Shifts in species richness, herbivore specialization, and plant resistance along elevation gradients. *Ecology and Evolution*, 2, 1818-1825.

Pellissier, L., Alvarez, N., Espíndola, A., Pottier, J., Dubuis, A., Pradervand, J. N., and Guisan, A. (2012). Phylogenetic alpha and beta diversities of butterfly communities correlate with climate in the western Swiss Alps. *Ecography*, 36, 541–550.

Pellissier L. et al. Past climate-driven range shifts and population genetic diversity in arctic plants. *Journal of Biogeography*, in press.

Rasmann, S., Pellissier, L., Defossez, E., Jactel, H., and Kunstler, G. (2013). Climate-driven change in plant–insect interactions along elevation gradients. *Functional Ecology*.

Rabiner N., L.Y. Juang (1993) Fundamentals of Speech Recognition. PTR Prentice-Hall, NJ.

Reynolds D., Rose R. (1995) Robust text-independent speaker identification using Gaussian mixture speaker models", IEEE Trans. On Speech and Audio Proc., 3, 72-83.

Riede, K. (1998) Acoustic monitoring of Orthoptera and its potential for conservation. *Journal of Insect Conservation*. 2, 217-223.

Roesti C. and Keist B. (2009) Die Stimmen der Heuschrecken. Haupt Verlag.

Sala, O. E. et al. (2000). Global biodiversity scenarios for the year 2100. *Science*, 287, 1770-1774.

Schwenker F, Dietrich C, Kestler HA, Riede K and Palm G. (2003) Radial basis function neural networks and temporal fusion for the classification of bioacoustic time series. *Neurocomputing*, 51, 265–275.

Specht D.F. (1990) Probabilistic Neural Networks, Neural Networks, 3, 109-118.

Stowell, D. and Plumbley, M. D. (2014). Automatic large-scale classification of bird sounds is strongly improved by unsupervised feature learning. PeerJ, 2, e488.

Sueur, J., Pavoine, S., Hamerlynck, O., and Duvail, S. (2008). Rapid acoustic survey for biodiversity appraisal. *PLoS One*, 3, e4065.

Tauber E. and Pener M. P. (2000) Song recognition in female bushcrickets *Phaneroptera nana*. *The Journal of Experimental Biology* 203, 597–603.

Tilman, D. (1999). Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. Proceedings of the National Academy of Sciences, 96(11), 5995-6000.

Zhang, J. et al. (2013). Managing and analysing big audio data for environmental monitoring. In Computational Science and Engineering (CSE), 2013 IEEE 16th International Conference on (pp. 997-1004). IEEE.

Zhu L. and Zhang Z., "Insect Sound Recognition Based on SBC and HMM," 2010 International Conference on Intelligent Computation Technology and Automation (ICICTA), vol.2, no., pp.544-548, 11-12 May 2010.