Organic & Biomolecular Chemistry

Accepted Manuscript

ROYAL SOCIETY OF CHEMISTRY

www.rsc.org/obc

Organic & Biomolecular Chemistry

Cite this: DOI: 10.1039/c0xx00000x
www.rsc.org/xxxxxx

PAPER

Facile and convenient sequential homobimetallic catalytic approach towards β-methylstyrenes. A one-pot Stille cross-coupling/isomerization strategy

Sebastián O. Simonetti,[a] Enrique L. Larghi[a] and Teodoro S. Kaufman*[a]

Received (in XXX, XXX) Xth XXXXXXXXX 201X, Accepted Xth XXXXXXXXX 201X
DOI: 10.1039/b000000x

An efficient one-pot synthetic approach towards β-methylstyrenes is reported. The transformation, based on sequential homobimetallic catalysis, involves a Stille cross-coupling reaction between aryl halides with allyltributylstannane, followed by an *in situ* Palladium-catalyzed conjugative isomerization. The reaction was optimized, and the best results were obtained with 10 mol% $Pd(PPh_3)_2Cl_2$, 8.0 equiv. LiCl, and 0.5 equiv. PPh_3 in diglyme, at 130ºC for 12 h. It was demonstrated that the reaction tolerates a wide variety of functional groups.

Introduction

Palladium-catalyzed cross-coupling reactions have become a highly significant field in modern arene chemistry, now being considered state of the art for C-C bond formation processes.[1]

The synthesis of β-methylstyrenes is of general interest because this motif is present in many natural products, such as the antibiotic agent fumimycin,[2a,b] the novel inhibitor of the enzymes lipoxygenase and aldose reductase nigerloxin,[2c,d] and the complex neolignan ratanhine, isolated from the medicinal plant *Ratanhiae radix*[2e,f] (Figure 1).

The β-methylstyrene scaffold is also found in pharmaceutically and technologically relevant compounds[3] such as a β-cathenin/tcf-4 inhibitor[3a] and the [l]benzothieno[3,2-*b*][l]benzothiophene derivative OSC5, useful for building photoelectric converting elements.[3c] In addition, β-methylstyrenes have been employed as precursors of more complex molecules,[4] as substrates for testing the scope and limitations of new chemical reagents[5] and as dehydrogenation agents.[6]

β-Methylstyrenes are commonly accessed by conjugative migration of the double bond of allylbenzenes. This transformation has been performed by treatment of the latter with bases (KF/Al_2O_3[7a] and K_2CO_3[7b]) or transition metal complexes (from Ti[8a,b] and Fe[8c,d] to softer Lewis acid derivatives of Rh,[9a] Ru,[9b,c] Ir,[10a] Pd,[10b,c] Pt[11a] and Ni[11b,c]). It has also been shown that bulky palladium hydride complexes promote the selective conversion of terminal alkenes into 2-alkenes.[12]

In spite of the widespread use of β-methylstyrenes, rather few methods have been disclosed for their direct synthesis from easily available starting materials, and employing C-C bond forming reactions to install the required three-carbon atom moiety, and many of them require special equipment, have scarce applicability or exhibit serious drawbacks.

These approaches include the cross coupling reaction of aryllithium, arylmagnesium and arylmanganese compounds with vinyl halides,[13] vinyl boronates,[14] and allyl or vinyl sulfones;[15] however, they should be performed under conditions that are

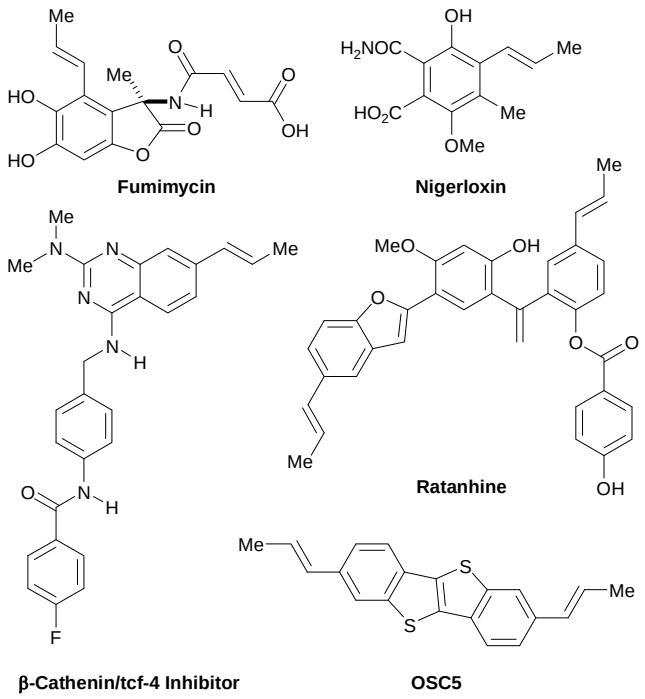


Figure 1. Selected natural and synthetic β-methylstyrene derivatives.

[a] Instituto de Química Rosario (IQUIR, CONICET-UNR) and Facultad de Ciencias Bioquímicas y Farmacéuticas, Universidad Nacional de Rosario, Suipacha 531, S2002LRK Rosario, Argentina. Tel/Fax: +54-341-4370477; E-mail: kaufman@iquir-conicet.gov.ar

† Electronic Supplementary Information (ESI) available: selected spectra of intermediates and final product. See DOI: 10.1039/b000000x/

compatible with relatively few functional groups.

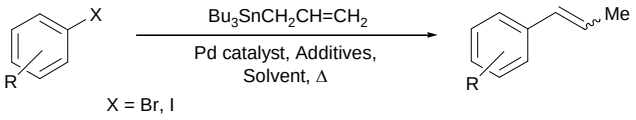
Other alternatives are the arylation of propyne involving a vinylborane cross-coupling/oxidation protocol under strongly basic conditions,[16] the iron-promoted arylation of propene with anilines[17a] and the electrochemically-assisted nickel-catalyzed reaction of aryl halides with propene.[17b] A Heck-type arylation of allylsilanes, furnishing β-methylstyrenes as side/unexpected products,[18] and a nickel catalyzed cross-coupling of modified alkyl and alkenyl Grignard reagents with aryl- and heteroaryl nitriles have also been disclosed.[19] However, this group of transformations seems to have a rather narrow scope and some of them give relatively low yields of product.

Propenylations with the aid of 1-propenyltributyltin,[20] allyl trifluoroborates,[21] vinylboronic acids (Suzuki-Miyaura cross coupling)[22] and allyl/vinyl boronates have been reported as alternatives,[23] but these are comparatively expensive reagents.

The conversion of allyl benzenoids into their corresponding 1-propenyl derivatives has been occasionally observed as a secondary process during Pd-catalyzed cross-couplings[24] since the initial reports of Stille's reaction.[25] Important amounts of the 1-propenyl derivatives (produced at the expense of their sought allyl congeners), were sometimes detected, especially when arenes carrying electron-withdrawing substituents were employed as starting materials.[26a] However, this outcome was qualified as a "very rare" and "unexpected" isomerization,[26b] and its usefulness as a synthetic transformation has surprisingly not been further explored.

During our recent synthesis of the structure originally assigned to the marine alkaloid aspergillitine,[27] we observed the conjugative migration of the double bond of a 7-allyl chromone intermediate to the related 1-propenyl derivative. Since this sequence took place in a completely atom-economical process and without addition of special reagents, and taking into account that tandem protocols are considered to be superior to stepwise procedures because they shorten the synthetic scheme, we considered optimizing the transformation towards the preparation of β-methylstyrenes.

Therefore, here we report a facile and convenient one-pot approach to the synthesis of β-methylstyrenes, as shown in Scheme 1, which involves a Palladium-catalyzed Stille cross-coupling reaction of aryl halides with allyltributylstannane, followed by an *in situ* double bond conjugative migration. The transformation was optimized and its scope and limitations were studied.



Scheme 1. Proposed one-pot synthesis of β-methylstyrenes.

Results and discussion

The easy accessibility and comparative inexpensiveness of allyltributyltin are advantageous for its use as a three carbon atoms source. Oppositely, (*E/Z*)-propenyl tributylstannanes are costly and not readily available,[28] also being acid-sensitive and prone to proto-destannylation.[29]

In order to find the proper reaction conditions, the Pd-catalyzed model reaction of 2-bromoanisole (**1a**) with allyltributyltin, employing 8.0 equiv. LiCl and 0.5 equiv. PPh_3, was first used to evaluate the catalytic activity of several Pd sources. Compound **1a** was selected for optimization of the transformation because it has an *ortho* electron donating group, which may hinder the reaction by exerting both, steric and electronic effects.

Among the catalysts tested, the results indicated that $Pd(PPh_3)_2Cl_2$ exhibited the best performance, furnishing 62% overall yield of a 35/65 mixture of 2-allylanisole (**2a**) and (*E/Z*)-1-methoxy-2-propenyl-benzene (**3a**, *E/Z*= 83/17) after 48 h at 130ºC in DMF (Table 1, entries 1-4). A good performance was also observed with the use of $Pd(PPh_3)_4$ as catalyst, in DMF at 130ºC. This catalyst afforded the product in 60% yield; the corresponding allyl/propenyl derivatives ratio was 2/98, with an *E/Z* relationship of 91/9 (entry 5).

Next, the effect of PPh_3, PBu_3 and Dppp and DavePhos as added phosphine ligands was examined, concluding that all of them were acceptable (entries 4 and 6-8), and that PPh_3 exhibited the best profile. Notably, DavePhos (0.5 equiv. regarding the amount of the Pd catalyst) gave a 71% combined yield of allyl/propenyl derivatives (ratio: 13/87) with an *E/Z* relationship of 85/15 (entry 6).

However, after analysis of these results it was concluded that the performances of $Pd(PPh_3)_4$ and DavePhos (entries 5 and 6) represented not highly significant differences; therefore, for price and convenience reasons their use was not further tested.

During the stage of solvent selection (entries 4 and 9-11), *N,N*-dimethylacetamide (DMA) and *N*-methyl pyrrolidone (NMP) allowed carrying out the transformation at higher temperatures; however, no meaningful improvements were observed.

On the other hand, diglyme (entry 11) proved to be a superior solvent, furnishing a more efficient conversion of the allyl intermediate **2a** into the corresponding β-methylstyrene derivative **3a**. This solvent had demonstrated to possess unique properties in previously reported Pd-catalyzed cross-couplings.[30]

Diglyme allowed shortening the reaction time up to to 12 h (entry 12), produced improvements in product yields, and easied the reaction work up. Attempts to further reduce the reaction time to 8 h or lower the temperature proved to be detrimental to the process performance, specifically diminishing the extent of the double bond conjugative migration stage (entries 13-15). Only 2-allylanisole (**2a**) was detected after heating 4 h at 90ºC (entry 16).

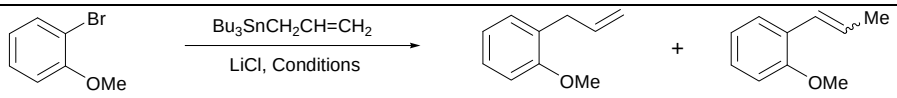
It was also found that LiCl is critically important for obtaining a successful transformation (entry 18). On the other hand, use of CsF in place of LiCl (DMF, 130ºC) slightly improved the reaction performance (58% yield, **2a**/**3a**: 6/94; *E/Z*: 91/9); however, the system proved to be incompatible with certain functional groups and study of its use was not further pursued.

In order to demonstrate the efficiency and scope of the present method, the optimized catalytic system was applied to a representative set of aryl halides, containing various substituents and displaying different functionalization patterns. The results (Table 2) revealed that, in general, the transformation proceeded in good overall yield.

Taking into account that the process entails two consecutive reactions, even the lowest performances represent the result of individual transformations taking place in around 75% yield.

Furthermore, the optimized conditions were compatible with several functional groups, including alkyl/aryl, ether, *N,N*-dimethylamino, ketone, ester, nitro and cyano moieties.

Table 1. Optimization of the reaction conditions.



1a **2a** **3a**

Entry Nº	Catalyst[a]	Ligand	Solvent	Temp. (ºC)	Time (h)	Yield (%)[b]	**2a**/**3a** (%)	*E/Z* (%)
1	$Pd(MeCN)_2Cl_2$	PPh_3	DMF	130	48	60	63/37	86/14
2	$Pd(OAc)_2$	PPh_3	DMF	130	48	93	71/29	80/20
3	$Pd_2(dba)_3$	PPh_3	DMF	130	48	30	34/64	86/14
4	$Pd(PPh_3)_2Cl_2$	PPh_3	DMF	130	48	62	35/65	83/17
5	$Pd(PPh_3)_4$	PPh_3	DMF	130	48	60	2/98	91/9
6	$Pd(PPh_3)_2Cl_2$	DavePhos	DMF	130	48	71	13/87	85/15
7	$Pd(PPh_3)_2Cl_2$	Dppp	DMF	130	48	68	63/37	81/19
8	$Pd(PPh_3)_2Cl_2$	PBu_3	DMF	130	48	55	58/42	86/14
9	$Pd(PPh_3)_2Cl_2$	PPh_3	DMA	140	48	56	14/86	84/16
10	$Pd(PPh_3)_2Cl_2$	PPh_3	NMP	160	24	43	93/7	91/9
11	$Pd(PPh_3)_2Cl_2$	PPh_3	Diglyme	130	48	36	0/100	92/8
12	$Pd(PPh_3)_2Cl_2$	PPh_3	Diglyme	130	12	59	4/96	100/0
13	$Pd(PPh_3)_2Cl_2$	PPh_3	Diglyme	130	8	65	63/37	90/10
14	$Pd(PPh_3)_2Cl_2$	PPh_3	Diglyme	110	12	65	17/83	90/10
15	$Pd(PPh_3)_2Cl_2$	PPh_3	Diglyme	90	12	76	51/49	90/10
16	$Pd(PPh_3)_2Cl_2$	PPh_3	Diglyme	90	4	80	100/0	-
17	$Pd(PPh_3)_2Cl_2$ (5%)	PPh_3	Diglyme	130	12	49	63/37	87/13
18[c]	$Pd(PPh_3)_2Cl_2$	PPh_3	Diglyme	130	12	49[d]	83/17	45/55

[a] Catalyst loading 10%.

[b] Yields after isolation and purification. Prior to purification, the crude mixture was analyzed by GC-MS and ^{1}H NMR, confirming that the yields of isolated product are a true reflection of the reaction outcome.

[c] Without addition of LiCl.

[d] Based on 55% of recovered starting material.

In addition, it was observed that the presence of functionalities *ortho* to the halide did not hinder the transformation and did not result in significatively lower yields of the corresponding β-methylstyrene products (entries 1 vs. 2 and 3 and 6 vs. 7).

However, a closer inspection revealed that the best results were obtained when the substrates carried electron withdrawing groups placed *para* to the halide (entries 4 and 5) and that compounds carrying electron withdrawing groups *ortho* to the halide exhibited better performances when compared with substrates having an electron releasing group at the same position (entries 1, 9 and 10).

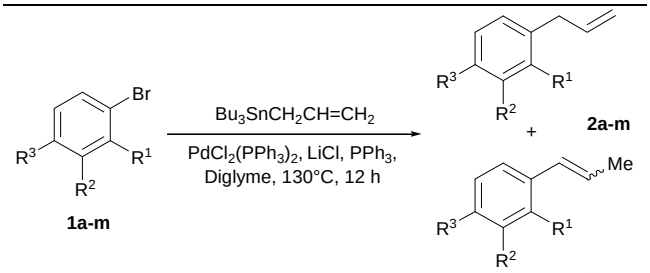
Although the exact details of the reaction mechanism of this transformation are still uncertain, a mechanistic picture can be proposed based on several observations made during this study. Firstly, the formation of the isomerized product should take place through the intermediacy of an allylbenzenoid species, resulting from an initial Stille cross-coupling reaction. These compounds were chromatographically detected and spectroscopically identified. In addition, 1-propenyl stannane should be ruled out as a reactant, since in the absence of aryl halide, the starting allylstannane proved to be remarkably stable under the optimized reaction conditions, not isomerizing to the related 1-propenyl stannane.[31]

That the double bond migration requires the presence of a Pd catalyst and it is not a merely thermal process was also assessed with a control experiment employing 4-allylanisole. It was observed that no conjugative isomerization took place under the standard conditions, in the absence of the catalyst.

These observations enable to speculate that an initial Stille cross-coupling reaction takes place between the aryl derivative (***i***) and the allylstannane (Scheme 2). It is known that the Stille reaction is promoted by a Pd^0 species, which can be formed *in situ* by partial reduction of the Pd^{II} catalyst by PPh_3 or by the stannane itself.[32]

After the well-established steps of oxidative addition of the substrate on the Pd complex (***ii***) and transmetallation with transfer of the allyl moiety to the Pd complex (***iii***), the latter may undergo reductive elimination to the allyl derivative (**2**), with either regeneration of the Pd^0 catalyst, or formation of an η^3-allyl hydride (***iv***).

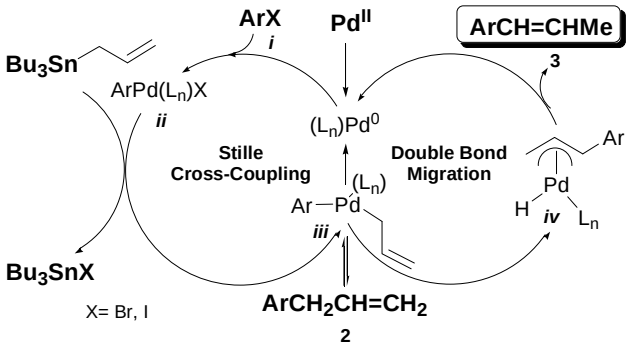
Table 2. One pot synthesis of β-methylstyrenes **3a-m**.



Entry	R_1	R_2	R_3	Yield (%)	Prod.	**2**/**3**	*E*/*Z*
1	OMe	H	H	59	**2a**/**3a**	4/96	100/0
2	H	OMe	H	65	**2b**/**3b**	4/96	92/8
3	H	H	OMe	62	**2c**/**3c**	3/97	95/5
4	H	H	CN	92	**2d**/**3d**	0/100	95/5
5	H	H	COMe	96	**2e**/**3e**	0/100	94/6
6	H	H	Me	76	**2f**/**3f**	0/100	100/0
7	Me	H	H	72	**2g**/**3g**	0/100	94/6
8	NO_2	H	OMe	56	**2h**/**3h**	0/100	90/10
9	CO_2Et	H	H	77[a]	**2i**/**3i**	0/100	100/0
10	CO_2Et	H	H	72	**2i**/**3i**	0/100	93/7
11	Ph	H	H	76	**2j**/**3j**	6/94	89/11
12	H	H	NMe_2	59	**2k**/**3k**	0/100	89/11
13	1-bromonaphthalene			76	**2l**/**3l**	9/91	100/0
14	9-bromophenanthrene			59	**2m**/**3m**	12/88	100/0

[a] The iodo derivative was employed.

The subsequent double-bond conjugative migration to yield the isomerized alkene product **3** should involve a β-hydride elimination.[33] Alternatively, the intermediate ***iv*** should give back the starting olefin (**2**) if the H returns to the same site it left.[34a]



Scheme 2. Proposed reaction mechanism.

The intermediacy of the allyl derivatives **2** in this transformation was unequivocally demonstrated with control experiments run with **2c**. As expected, when **2c** was exposed to $Pd(PPh_3)_2Cl_2$ and LiCl in diglyme, in the presence of PPh_3, the reaction met with failure, due to the reduction of the Pd by the phosphine.[32b] However, omission of PPh_3 provided 78% yield of **3c**, when **2c** was submitted to the optimizad reaction conditions.

Taking into account that the palladium source is added in catalytic amounts and that complete conversion of the starting material into the allyl derivative **2** has been clearly observed at the earliest stages of the transformation, it should be concluded that the allylarene derivative **2** could also be a source of intermediate ***iii***, acting as a proxy towards **3**.

Observation of **2** as a first reaction product and its conversion into **3** under higher temperature conditions can be regarded as a result of a process in which the allyl derivative **2** is the kinetically controlled product of a sequence, in which it is driven towards the thermodynamic, most stable product **3** when heated for a longer time.

Precipitation of palladium metal has been associated to the isomerization of allyl moieties;[34b] in our case, however, it was observed that the addition of PPh_3 avoids precipitation of palladium black,[34c] while ensuring good overall yields.

On the other hand, LiCl may participate of the mechanism as a source of chloride ligand, stabilizing the Pd intermediates and turning more efficient the cross-coupling stage. It has been demonstrated the LiCl is a powerful reaction rate accelerant, turning the Pd catalyst more active towards transmetalation and more prone to oxidative addition. Furthermore, LiCl enhances the polarity of the solvent, enhancing the leaving ability of anionic ligands. As an additive, it has been found necessary when the transformation is run in ethereal solvents.[35a,b]

Interestingly, the presence of Bu_3SnCl was detected during GC-MS monitoring of the reactions (M^+ = 326, with its characteristic isotopic cluster).

The influence of diglyme as the reaction solvent may stem from its ability to exchange with the Pd-ligands at various stages of the cycle, also stabilizing the resulting intermediates. It has been found that diglyme has an accelerating effect on some Pd-catalyzed C-C bond forming processes. The ether- *O*-donor atoms may act initially by blocking the soft metal centers; in this way, at a later stage these are more rapidly substituted by the substrates, since Pd^{II} has a low affinity for neutral *O*-ligands. Similarly, these solvent properties may offer a more rapid product decomplexation step, favoring the whole process.[35c]

Globally observed, the transformation may be regarded as a novel case of sequential homobimetallic catalysis.[36] This is a recent concept designed to describe a condition where a transition metal catalyst, with the metal in a certain oxidation state, catalyzes a given reaction to yield a product, which *in situ* undergoes a subsequent transformation, catalyzed by another complex of the same metal, but in a different oxidation state.[37]

In the current case, the Pd^0-catalyzed Stille cross-coupling reaction is concatenated with a Pd^{II}-catalyzed conjugative migration process, leading to the resulting β-methylstyrenes. Noteworthy, examples of this new but highly useful paradigm of reactions in tandem are scarce.

Conclusions

In conclusion, we have developed a facile and convenient alternative for the synthesis of β-methylstyrenes through an efficient sequential homobimetallic palladium catalyzed one-pot process.

The transformation entails two steps in tandem, namely a Stille cross-coupling reaction, followed by an *in situ* Pd-assisted double bond conjugative isomerization.

In light of its operational simplicity, tolerance to a wide range

of functional groups, good overall yields and satisfactory regioselectivity, it is expected that this strategy will find wide use in organic synthesis of complex molecules, including natural products.

Experimental section

General information

The reactions were carried out under anhydrous Argon atmospheres, employing oven-dried glassware. Dry DMF, NMP and DMA were prepared by distillation from anhydrous BaO; xylenes and diglyme were distilled from Na°/benzophenone ketyl. Anhydrous solvents were stored in dry Young ampoules. The other reagents were used as received.

In the conventional purification procedure, the crude material was submitted to flash column chromatography with silica gel 60 H (particle size 63–200 μm). Elution was carried out with mixtures of hexane-Et_2O, under positive pressure of N_2 and employing gradient of solvent polarity techniques.

All new compounds gave single spots when run on TLC plates of Kieselgel 60 GF_{254}, employing different hexane-Et_2O and hexane-EtOAc solvent systems. Chromatographic spots were detected by exposure of the plates to UV light (254 nm), followed by spraying with ethanolic *p*-anisaldehyde/sulfuric acid reagent and careful heating.

Apparatus

The IR spectra were recorded with a Shimadzu Prestige 21 spectrophotometer, as thin films held between NaCl cells.

The ^1H and ^{13}C NMR spectra were acquired at 300.13 and 75.48 MHz respectively, on a Bruker Avance 300 spectrometer. The resonances of $CHCl_3$ in $CDCl_3$ (δ 7.26 and 77.0 for ^1H and ^{13}C NMR, respectively) were used as internal standards. Chemical shifts are reported in parts per million in the δ scale and the magnitudes of the coupling constants (*J*) are given in Hertz. DEPT 135 and DEPT 90 experiments aided the interpretation of the fully decoupled ^{13}C NMR spectra. In special cases, 2D-NMR experiments (COSY, HSQC and HMBC) were also employed.

The GC-MS experiments were carried out with a Shimadzu QP2010 *plus* instrument equipped with a AOC-20i autosampler. The chromatographic runs were performed in the split injection mode (ratio: 50), on a SPB-1 column (28.5 m × 0.25 mm × 0.25 μm), with an helium flow of 1.05 mL/min. The oven temperature program as as follows: T_{Init}= 50 ºC (3 min.); then ΔT= 5 ºC/min up to T_1= 180 ºC; then ΔT= 20 ºC/min up to T_{End}= 310 ºC.

Low resolution mass spectra were obtained under the following conditions: $T_{Interface}$= 300 ºC; $T_{Ion\ source}$= 230 ºC; Solvent cut time= 8 min; Ionization voltage= 70 eV. The mass spectra were compared against the NIST08 library. Diphenyl ether (Aldrich 99.5 %) was employed as internal standard for interpretation, comparison and quantitative purposes. The quality of the results was assessed against simultaneous ^1H NMR analysis of a small sample (1-2 mg) of the reaction.

The high resolution mass spectra were obtained on a Bruker MicroTOF-Q II instrument. Detection of the ions was performed with electrospray ionization in positive ion mode.

General procedure for the preparation of β-Methylstyrenes: Allyltributyltin (1.2 equiv.) was added to a degassed solution of the aryl halide (1 equiv.), anhydrous LiCl (8 equiv.), Ph_3P (0.5 equiv.) and $Pd(Ph_3P)_2Cl_2$ (0.1 equiv.) in anhydrous diglyme (final concentration *ca.* 0.15 M). The mixture was heated at 130 °C during 14 h under an argon atmosphere until complete consumption of the starting material as ascertained by GC analysis. The reaction was left to reach room temperature, when it was diluted with Et_2O (10 mL) and treated with a saturated solution of KF (5 mL). The mixture was stirred during 30 min. in order to quench the organotin-derivatives. The organic phase was successively washed with brine (2 × 5 mL) and H_2O (2 × 5 mL). The organics were filtered through a short pad of a 1:1 mixture of Florisil and Celite and dried over Na_2SO_4 prior to concentration under reduced pressure. Column chromatography of the residue gave the corresponding propenyl derivatives.

For the more volatile compounds **3f** and **3g**, the work-up was carried out as follows: The reaction was diluted with a 1:1 mixture of pentane and hexane (10 mL) and transferred to a separation flask. The organics were sequentially treated with a saturated solution of KF (5 mL) during 15 min., brine (5 mL) and H_2O (2 × 5 mL). The organic phase was then filtered through a short pad of Celite and silica gel (1:1, w/w), washing with pentane (10 mL). The liquids were dried over Na_2SO_4 and concentrated under a slow stream of nitrogen.

(*E*)-1-Methoxy-2-(prop-1-enyl)benzene (3a)[38a,b]

Yield = 59%; *E/Z* = 100:0; colourless oil. IR (Film, ν): 2924, 2852, 1463, 1456, 1437, 1244, 1119, 750, 721 and 694 cm^{-1}. ^1H NMR (δ): 1.90 (dd, *J* = 1.4 and 6.6, 3H), 3.84 (s, 3H), 6.22 (dq, *J* = 6.6 and 16.0, 1H), 6.72 (dd, *J* = 1.4 and 16.0, 1H), 6.85 (d, *J* = 8.2, 1H), 6.90 (t, *J* = 7.6, 1H), 7.18 (dt, *J* = 1.5 and 7.6, 1H) and 7.39 (dd, *J* = 1.5, 7.6, 1H). ^{13}C NMR (δ): 18.9, 55.4, 110.7, 120.6, 125.6, 126.4, 126.6, 127.7, 133.2 and 156.2. EI-MS (*m/z*, %): 148 (M^+, 100), 147 (10), 133 (22), 119 (55), 117 (33), 115 (46), 105 (69), 103 (26), 91 (83), 79 (26) and 77 (34).

(*E*)-1-Methoxy-3-(prop-1-enyl)benzene (3b)[38c,d]

Yield = 65%; *E/Z* = 92:8; colourless oil. IR (Film, ν): 2922, 2851, 1599, 1578, 1489, 1464, 1454, 1435, 1288, 1263, 1252, 1155, 1047, 964, 768 and 648 cm^{-1}. ^1H NMR (δ): 1.88 (dd, *J* = 1.2 and 6.4, 3H), 3.81 (s, 3H), 6.23 (dq, *J* = 6.4 and 15.7, 1H), 6.38 (d, *J* = 15.7, 1H), 6.75 (dd, *J* = 2.0 and 7.9, 1H), 6.87 (t, *J* = 2.1, 2H), 6.93 (dd, *J* = 1.9 and 7.7, 1H) and 7.20 (t, *J* = 7.8, 1H). ^{13}C NMR (δ): 18.4, 55.2, 111.2, 112.3, 118.5, 121.0, 126.1, 129.4, 139.4 and 159.8. EI-MS (*m/z*, %): 148 (M^+, 36), 147 (16), 117 (64), 116 (25), 115 (45), 105 (63), 103 (38), 92 (14), 91 (94), 89 (26), 79 (69), 78 (48) and 77 (100).

(*E*)-1-Methoxy-4-(prop-1-enyl)benzene (3c)[39a,d]

Yield = 62%; *E/Z* = 95:5; colourless oil. IR (Film, ν): 2924, 2851, 1732, 1607, 1512, 1456, 1377, 1174 and 1034 cm^{-1}. ^1H NMR (δ): 1.85 (dd, *J* = 1.6 and 6.6, 3H), 3.80 (s, 3H), 6.09 (dq, *J* = 6.6, 15.8, 1H), 6.35 (dd, *J* = 1.5 and 15.8, 1H), 6.83 (d, *J* = 8.8, 2H) and 7.26 (d, *J* = 8.8, 2H). ^{13}C NMR (δ): 18.4, 55.3, 113.9, 123.5, 126.9, 130.3, 130.8 and 158.6. EI-MS (*m/z*, %): 148 (M^+, 16), 119 (42), 115 (43), 105 (79), 103 (30), 91 (100), 79 (42), 78 (23) and 77 (56).

(*E*)-4-(Prop-1-enyl)benzonitrile (3d)[39e,f]

Yield = 92%; *E/Z* = 95:5; colourless oil. IR (Film, ν): 3059, 2986, 2930, 2230, 1701, 1609, 1504, 1408, 1379, 1202, 1119, 1107, 1018, 843 and 820 cm^{-1}. ^1H NMR (δ): 1.92 (d, *J* = 5.9, 3H), 6.31-6.44 (m, 2H), 7.38 (d, *J* = 8.3, 2H) and 7.55 (d, *J* = 8.3, 2H). ^{13}C NMR (δ): 18.6, 109.9, 119.9, 126.3 (2C), 129.8, 130.2, 132.3 (2C) and 142.4. EI-MS (*m/z*, %): 143 (M^+, 100), 142 (72), 140 (16), 117 (15), 116 (85), 115 (79), 89 (26) and 76 (13).

(*E*)-1-[4-(Prop-1-enyl)phenyl]ethanone (3e)[40a,b]

Yield = 96%; *E/Z* = 94:6; colourless oil. IR (Film, ν): 2914, 1674, 1603, 1409, 1360, 1267, 1180, 958, 852, 789 and 590 cm^{-1}. ^1H NMR (δ): 1.91 (d, *J* = 5.2, 3H), 2.57 (s, 3H), 6.32-6.47 (m, 2H), 7.39 (d, *J* = 8.4, 2H) and 7.88 (d, *J* = 8.4, 2H). ^{13}C NMR (δ): 18.7, 26.5, 125.8 (2C), 128.7 (2C) 129.1, 130.3, 135.4, 142.6 and 197.6. EI-MS (*m/z*, %): 160 (M^+, 33), 146 (10), 145 (100), 117 (25), 116 (12), 115 (59) and 91 (30).

(*E*)-1-Methyl-4-(prop-1-enyl)benzene (3f)[23a,39f,40c,d]

Yield = 76%; *E/Z* = 100:0; colourless oil. IR (Film, ν): 3023, 2921, 1638, 1551, 1432, 1110, 1015, 990, 962, 802 and 776 cm^{-1}. ^1H NMR (δ): 1.89 (dd, *J* = 1.2 and 6.5, 3H), 2.34 (s, 3H), 6.20 (dq, *J* = 6.5 and 15.8, 1H), 6.39 (d, *J* = 15.8, 1H), 7.24 (d, *J* = 8.3, 2H) and 7.37 (d, *J* = 8.3, 2H). ^{13}C NMR (δ): 18.5, 21.1, 124.6, 125.7 (2C), 129.2 (2C), 130.9, 135.2 and 136.4. EI-MS (*m/z*, %): 132 (M^+, 62), 117 (100), 115 (45), 105 (9), 91 (32) and 77 (10).

(*E*)-1-Methyl-2-(prop-1-enyl)benzene (3g)[39d]

Yield = 72%; *E/Z* = 94:6; Colourless oil. IR (Film, ν): 3023, 2921, 1638, 1551, 1432, 1110, 1015, 990, 962, 802 and 776 cm^{-1}. ^1H NMR (δ): 1.89 (dd, *J* = 1.2 and 6.5, 3H), 2.34 (s, 3H), 6.20 (dq, *J* = 6.5 and 15.8, 1H), 6.39 (d, *J* = 15.8, 1H), 7.04 (d, *J* = 7.6, 1H), 7.12 (t, *J* = 7.6, 1H), 7.24 (d, *J* = 8.3, 1H) and 7.35 (t, *J* = 7.6, 1H). ^{13}C NMR (δ): 18.5, 21.1, 124.6, 125.7 (2C), 129.2 (2C), 130.9, 135.2 and 136.4. EI-MS (*m/z*, %): 132 (M^+, 62), 131 (14), 117 (100), 116 (15),115 (51), 91 (34), 93 (28) and 91 (56).

(*E*)-4-Methoxy-2-nitro-1-(prop-1-enyl)benzene (3h)

Yield = 56%; *E/Z* = 90:10; Yellowish oil. IR (Film, ν): 2914, 1674, 1651, 1602, 1409, 1360, 1267, 1180, 958, 852 and 789 cm^{-1}. ^1H NMR (δ): 1.91 (dd, *J* = 0.9 and 6.6, 3H), 3.85 (s, 3H), 6.13 (dq, *J* = 6.6 and 15.9, 1H), 6.78 (d, *J* = 15.9, 1H), 7.08 (dd, *J* = 2.6 and 8.7, 1H), 7.38 (d, *J* = 2.6, 1H) and 7.47 (d, *J* = 8.7Hz, 1H). ^{13}C NMR (δ): 18.3, 55.5, 108.2, 108.7, 119.6, 125.6, 129.1, 129.2, 147.8 and 158.4 EI-MS (*m/z*, %): 193 (M^+, 24), 176 (10), 151 (58), 150 (100), 133 (20), 122 (47), 121 (21), 115 (29), 107 (22), 106 (30), 105 (31), 104 (20), 103 (59), 94 (36), 93 (28), 91 (56) and 77 (92). HRMS (ESI–TOF, *m/z*) Found: 216.06311; $C_{10}H_{11}NNaO_3^+$ requires 216.0637.

(*E*)-Ethyl 2-(prop-1-enyl)benzoate (3i)

Procedure A: From the aryl iodide.- Yield = 77%; *E/Z* = 100:0; colourless oil. IR (Film, ν): 2980, 1714, 1479, 1444, 1279, 1246, 1132, 1099, 1072 and 964 cm^{-1}. ^1H NMR (δ): 1.39 (t, *J* = 7.1, 3H), 1.92 (dd, *J* = 1.7 and 6.6, 3H), 4.36 (q, *J* = 7.1, 2H), 6.14 (dq, *J* = 7.1 and 15.7, 1H), 7.14 (dd, *J* = 1.5 and 15.7, 1H), 7.25 (dt, *J* = 0.9 and 7.2, 1H), 7.42 (dt, *J* = 1.2 and 7.5, 1H), 7.51 (d, *J* = 7.9, 1H), 7.83 (dd, *J* = 1.2 and 7.9, 1H). ^{13}C NMR (δ): 14.3, 18.8, 60.9, 126.4, 127.1, 128.4, 129.5, 129.7, 130.1, 131.8, 139.5 and 167.7. EI-MS (*m/z*, %): 190 (M^+, 49), 175 (46), 147 (86), 145 (47), 144 (24), 117 (67), 116 (45), 115 (100) and 91 (37). HRMS (ESI–TOF, *m/z*) Found: 191.1067; $C_{12}H_{15}O_2^+$ $[M+H]^+$ requires 191.1072.

Procedure B: From the aryl bromide.- Yield = 72%; *E/Z* = 93:7; colourless oil. IR, NMR and EI-MS spectra fully agree with those of **3i** obtained according to Procedure A.

(*E*)-2-(Prop-1-enyl)-biphenyl (3j)[41]

Yield = 76%; *E/Z* = 89:11; colourless oil. IR (Film, ν): 3061, 3040, 2928, 2914, 2851, 1584, 1487, 1236, 1163, 1072, 1022, 962, 866, 785, 748 and 691 cm^{-1}. ^1H NMR (δ): 2.01 (dd, *J* = 1.7 and 6.6, 3H), 6.26 (dq, *J* = 6.6 and 15.4, 1H), 7.15 (dd, *J* = 1.8 and 15.4, 1H) and 7.16-8.16 (m, 9H). ^{13}C NMR (δ): 19.0, 123.5, 124.0, 125.6, 125.7, 125.8, 127.2, 128.2, 128.3, 128.4, 128.6, 131.1, 133.6, 135.8 and 158.3. EI-MS (*m/z*, %): 194 (M^+, 34), 179 (100), 178 (54), 165 (16), 152 (7) 115 (6), 89 (18), 83 (12) and 76 (9).

(*E*)-Dimethyl-(4-propenyl-phenyl)-amine (3k)[23a,40c,d]

Yield = 57%; *E/Z* = 89/11; yellow-pale oil. IR (Film, ν): 2924, 1732, 1861, 1611, 1520, 1487, 1350, 1234 and 1165 cm^{-1}. ^1H NMR (δ): 1.85 (dd, *J* = 1.4 and 6.6, 3H), 2.94 (s, 6H), 6.03 (dq, *J* = 6.6 and 15.2, 1H), 6.32 (dd, *J* = 1.4 and 15.2, 1H), 6.68 (d, *J* = 8.8, 2H) and 7.23 (t, *J* = 8.8, 2H). ^{13}C NMR (δ): 18.4, 40.7 (2C), 116.7, 121.4 (2C), 123.2 (2C), 126.8, 130.7 (2C) and 149.6. EI-MS (*m/z*, %): 161 (M^+, 100), 160 (76), 145 (15), 144 (10), 134 (19), 118 (12), 117 (33), 115 (32), 91 (29) and 77 (19).

(*E*)-1-(Prop-1-enyl)naphthalene (3l)[42a,b]

Yield = 68%; *E/Z* = 81:19; colourless oil. IR (Film, ν): 3061, 3040, 2928, 2914, 2851, 1584, 1487, 1236, 1163, 1072, 1022, 962, 866, 785, 748 and 691 cm^{-1}. ^1H NMR (δ): 1.83 (dd, *J* = 1.6 and 6.5, 3H), 6.20 (dq, *J* = 6.5 and 15.7, 1H), 6.42 (d, *J* = 15.7, 1H), 7.24 (d, *J* = 8.3, 2H), 7.37 (d, *J* = 8.3, 2H), 7.48 (dt, *J*= 1.4 and 8.3, 1H), 7,60 (d, *J*= 7.0, 1H) and 7.63 (dt, *J*= 1.5 and 8.1, 1H). ^{13}C NMR (δ): 18.7, 125.8, 126.5, 126.7, 126.8, 127.2, 127.3, 127.4, 128.8, 130.2, 136.0, 140.2 and 141.3. EI-MS (*m/z*, %): 168 (M^+, 50), 167 (27), 165 (27), 154 (13), 153 (100), 152 (36), 83 (17) and 82 (14).

(*E*)-9-(Prop-1-enyl)phenanthrene (3m)[42c,d]

Yield = 69%; *E/Z* = 88:12; colourless oil. IR (Film, ν): 3057, 3018, 2924, 2851, 1597, 1493, 1450, 1433, 1242, 962, 812, 744, 735, 723 and 618 cm^{-1}. ^1H NMR **(δ)**: 2.04 (dd, *J* = 1.7 and 6.6, 3H), 6.33 (dq, *J* = 6.6 and 16.1, 1H), 7.13 (d, *J* = 16.1, 1H), 7.37 (d, *J* = 8.3, 2H), 7.75 (s, 1H), 7.76 (d, *J* = 5.7, 1H), 7.85-7.92 (m,

2H), 8.18 (dd, J = 0.9 and 8.3, 1H) and 8.64-8.74 (m, 4H). ^{13}C NMR (δ): 18.9, 122.5, 122.7, 123.0, 124.3, 124.8, 126.9, 128.4, 128.6, 128.7, 129.3, 129.9, 130.3, 130.8, 132.0, 132.1 and 134.7. EI-MS (*m/z*, %): 218 (M^+, 58), 217 (24), 215 (19), 204 (17), 203 (100), 202 (49), 109 (12), 108 (34), 107 (19), 101 (36), 100 (10), 95 (32) and 94 (10).

Acknowledgements

The authors thank Argentine National Research Council (CONICET) and National Agency for the Promotion of Science and Technology (ANPCyT) for financial support (PIP 2011-0479 and PICT 2011-0399). S. Tindiglia, P. Duché and G. Marcuzzi are acknowledged for running NMR and GC-MS spectra and Drs. V. and I. Dragutan (Romanian Academy, Romania) are thanked for helpful discussions regarding the reaction mechanism. S.O.S. acknowledges CONICET for his fellowship.

References and notes

1 a) A. Molnár, *Palladium-Catalyzed Coupling Reactions.* Wiley, New York, USA, 2013; b) C. C. C. Johansson Seechurn, M. O. Kitching, T. J. Colacot and V. Snieckus, *Angew. Chem. Int. Ed.*, 2012, **51**, 5062–5085; c) K. C. Nicolaou, P. G. Bulger and D. Sarlah, *Angew. Chem. Int. Ed.*, 2005, **44**, 4442–4489.

2 a) G. P. Gross and S. Bräse, *Chem. Eur. J.*, 2010, **16**, 12660–12667; b) P. J. Gross, F. Furche, M. Nieger and S. Bräse, *Chem. Commun.,* 2010, **46**, 9215–9217; c) K. C. Rao, S. Divakar, K. N. Babu, A. G. Rao, N. G. Karanth and A. P. Sattur, *J. Antibiotics,* 2002, **55**, 789–793; d) K. C. Sekhar Rao, N. G. Karanth and A. P. Sattur, *Proc. Biochem.*, 2005, **40**, 2517–2522; e) E. P. Gillis and M. D. Burke, *J. Am. Chem. Soc.* 2007, **129**, 6716–6717; f) A. Arnone, V. Di Modugno, G. Nasini, O. V. De Pava, *Gazz. Chim. Ital.*, 1990, **120**, 397–401.

3 a) A. Venkatesan, C. Dehnhardt, Z. Chen, O. Santos, E. Santos, K. Curran, S. Ayral-Kaloustian and L. Chen, Patent WO 2008/086462, 2008; b) J. A. Seijas, M. P. Vázquez-Tato, C. Entenza, M. M. Martínez, M. G. Onega and S. Veiga, *Tetrahedron Lett.*, 1998, **39**, 5073–5076; c) D. Goto, M.Torii, T. Horiuchi, T. Aruga, H. Ikuno, T. Sagisaka, S. Yamamoto, T. Orito, M. Mohri, T. Okada, T. Kato and S. Matsumoto. Patent WO 2009/128559, 2009.

4 a) G. W. Kabalka, Z. Wu and Y. Ju, *Tetrahedron Lett.*, 2003, **44**, 1187–1189; b) P. Mondal, L. Thander and S. K. Chattopadhyay, *Tetrahedron Lett.*, 2012, **53**, 1328–1331; c) B. Lantaño, J. M. Aguirre, E. A. Ugliarolo, M. L. Benegas and G. Y. Moltrasio, *Tetrahedron*, 2008, **64**, 4090–4102; d) O. Brücher, U. Bergsträßer, H. Kelm, J. Hartung, M. Greb, I. Svoboda and S. Fuess, *Tetrahedron*, 2012, **68**, 6968–6980. e) B. B. Snider and J. F. Grabowski, *Tetrahedron Lett.*, 2005, **46**, 823–825; f) B. B. Snider and J. F. Grabowski, *Tetrahedron*, 2006, **62**, 5171–5177.

5 a) K.-I. Fujita, S. Umeki, M. Yamazaki, T. Ainoya, T. Tsuchimoto and H. Yasuda, *Tetrahedron Lett.*, 2011, **52**, 3137–3140; (b) K.-I. Fujita, T. Ainoya, T. Tsuchimoto and H. Yasuda, *Tetrahedron Lett.*, 2010, **51**, 808–810; c) N. J. Kerrigan, H. Müller-Bunz and D. G. Gilheany, *J. Mol. Catal. A*, 2005, **227**, 163–172; d) C. T. Dalton, K. M. Ryan, I. J. Langan, E. J. Coyne and D. G. Gilheany, *J. Mol. Catal. A*, 2002, **187**, 179–187; e) Z. Yang, J. C. Lorenz and Y. Shi, *Tetrahedron Lett.*, 1998, **39**, 8621–8624; f) D. P. Allen, C. M. Crudden, L. A. Calhoun, R. Wang and A. Decken, *J. Organomet. Chem.*, 2005, **690**, 5736–5746; g) S. Minakata, M. Nishimura, T. Takahashi, Y. Oderaotoshi and M. Komatsu, *Tetrahedron Lett.*, 2001, **42**, 9019–9022; h) R. Vyas, G.-Y. Gao, J. D. Harden and X. P. Zhang, *Org. Lett.*, 2004, **6**, 1907–1910.

6 J. Schoepfer, B. Gay, N. End, E. Muller, G. Scheffel, G. Caravatti and P. Furet, *Bioorg. Med. Chem. Lett.*, 2001, **11**, 1201–1203.

7 a) T. X. T. Luu, T. T. Lam, T. N. Le and F. Duus, *Molecules*, 2009, **14**, 3411–3424; b) S. R. Waldman, A. P. Monte, A. Bracey and D. E. Nichols, *Tetrahedron Lett.*, 1996, **37**, 7889–7892.

8 a) G. W. Parshall and S. D. Ittel, Homogeneous Catalysis, 2nd ed.; Wiley:New York, USA, 1992; pp 9–24; b) H. S. Lee and G. Y. Lee, *Bull. Korean Chem. Soc*., 2005, **26**, 461–462; c) M. R. Reddy and M. Periasamy, *J. Organomet. Chem.* 1995, **491**, 263–266; d) M. Mayer, W. M. Czaplik and A. J. von Wangelin, *Adv. Synth. Catal.*, 2010, **352**, 2147–2152.

9 a) M. S. Fichman, Y. Sasson and J. Blum, *J. Mol. Catal. A*, 1997, **126**, 27–36; b) S. K. Sharma, V. K. Srivastava and R. V. Jasra, *J. Mol. Catal. A*, 2006, **245**, 200–209; c) T. J. Donohoe, T. J. C. O'Riordan and C. P. Rosa, *Angew. Chem. Int. Ed.*, 2009, **48**, 1014–1017.

10 a) I. R. Baxendale, A.-L. Lee and S. V. Ley, *J. Chem. Soc., Perkin Trans. 1*, 2002, 1850–1857; b) R. Jennerjahn, I. Piras, R. Jackstell, R. Franke, K.-D. Wiese and M. Beller, *Chem. Eur. J.*, 2009, **15**, 6383–6388; c) I. S. Kim, G. R. Dong and Y. H. Jung, *J. Org. Chem.*, 2007, **72**, 5424–5426.

11 a) A. Scarso, M. Colladon, P. Sgarbossa, C. Santo, R. A. Michelin and G. Strukul, *Organometallics*, 2010, **29**, 1487–1497; b) O. P. Tkachenko, L. M. Kustov, S. A. Nikolaev, V.V. Smirnov, K. V. Klementiev, A. V. Naumkin, I. O. Volkov, A. Y. Vasilkov and D. Y. Murzin, *Top. Catal.*, 2009, **52**, 344–350; c) C. M. Jinesh, C. A. Antonyraj and S. Kannan, *Appl. Clay Sci.*, 2010, **48**, 243–249.

12 D. Gauthier, A. T. Lindhardt, E. P. K. Olsen, J. Overgaard and T. Skrydstrup, *J. Am. Chem. Soc.*, 2010, **132**, 7998–8009.

13 a) S. Haraki, A. Hayashi, Y. Moriwaki, A. Nagaki, N. Takabayashi, J.-I. Yoshida and A. Kenmoku, *Chem. Asian J.*, 2012, **7**, 1061–1068; b) H. Avedissian and G. Cahiez, *Tetrahedron Lett.*, 1998, **39**, 6159–6162; c) H. Avedissian and G. Cahiez, *Synthesis*, 1998, 1199–1205; d) G. Cahiez and S. Marquais, *Tetrahedron Lett.*, 1996, **37**, 1773–1776; e) A. Kageyama, H. Kondo, H. Nagashima, Y. Yamaguchi, M.-A. Haga and K. Kirchner, *Bull. Chem. Soc. Japan*, 2001, **74**, 1927–1937.

14 H. C. Brown, D. Basavaiah, S. U. Kulkarni, N. G. Bhat and J. V. N. V. Prasad, *J. Org. Chem.*, 1988, **53**, 239–246.

15 a) J.-L. Fabre, M. Julia and J.-N. Verpeaux, *Bull. Soc. Chim. Fr.*, 1985, 762–771; b) Y. Gai, M. Julia and J.-N. Verpeaux, *Bull. Soc. Chim. Fr.*, 1996, **133**, 805–816.

16 J. C. Colberg, A. Rane, J. A. Soderquist and J. Vaquer, *J. Am. Chem. Soc.*, 1993, **115**, 6065–6071.

17 a) F. Akiyama, H. Miyazaki, K. Kaneda, S. Teranishi, Y. Fujiwara, M. Abe and H. Taniguchi, *J. Org. Chem.*, 1980, **45**, 2359–2361; b) Y. Rollin, G. Meyer, M. Troupel, J.-F. Fauvarque and J. Perichon, *J. Chem. Soc., Chem. Commun.*, 1983, 793–794.

18 a) T. Jeffery, *Tetrahedron Lett.*, 2000, **41**, 8445–8449; b) U. Martínez-Estíbalez, N. Sotomayor and E. Lete, *Tetrahedron Lett.* 2007, **48**, 2919–2922.

19 a) J. A. Miller and J. W. Dankwardt, *Tetrahedron Lett.*, 2003, **44**, 1907–1910; b) J. W. Dankwardt, J. A. Miller and J. M. Penney, *Synthesis*, 2003, 1643–1648.

20 a) T. Kumemura, T. Choshi, A. Hirata, M. Sera, Y. Takahashi, J. Nobuhiro and S. Hibino, *Chem. Pharm. Bull.*, 2005, **53**, 393–397; b) G. P. Roth and C. E. Fuller, *J. Org. Chem.*, 1991, **56**, 3493–3496; (c) A. J. Borchardt, C. Beauregard, T. Cook, R. L. Davis, D. A. Gamache and J. M. Yanni, Patent WO 2010/030785, 2010.

21 M. Al-Masum and S. Alam, *Tetrahedron Lett.*, 2009, **50**, 5201–5204.

22 a) F. Berthiol, H. Doucet, E. Peyroux and M. Santelli, *Eur. J. Org. Chem.*, 2004, 1075–1082; b) V. H. Gessner, S. G. Koller, C. Strohmann, A.-M. Hogan and D. F. O'Shea, *Chem. Eur. J.*, 2011, **17**, 2996–30041.

23 K. Nilsson and A. Hallberg, *Acta Chem. Scand. B*, 1987, **41**, 569–576.

24 a) W. Su, S. Urgaonkar, P. A. McLaughlin and J. G. Verkade, *J. Am. Chem. Soc.*, 2004, **126**, 16433–16439; b) B. Mariampillai, C. Herse and M. Lautens, *Org. Lett.*, 2005, **7**, 4745–4747; c) J. B. Bremner, P. A. Keller, S. G. Pyne, A. D. Robertson, B. W. Skelton, A. H. White and H. M. Witchard, *Aust. J. Chem.*, 2000, **53**, 535–540; d) K. Hirano, K. Fujita, H. Yorimitsu and K. Oshima, *Synlett*, 2005, 1787–1788.

25 a) J. K. Stille and B. L. Groh, *J. Am. Chem. Soc.*, 1987, **109**, 813–817; b) A. M. Echavarren and J. K. Stille, *J. Am. Chem. Soc.*, 1987, **109**, 5478–5486.

26 a) W. Su, S. Urgaonkar and J. G. Verkade, *Org. Lett.*, 2004, **6**, 1421–1424; b) W. H. Pearson and M. J. Postich, *J. Org. Chem.*, 1994, **59**, 5662–5671.

27 S. O. Simonetti, E. L. Larghi, A. B. J. Bracca and T. S. Kaufman, *Org. Biomol. Chem.*, 2012, **10**, 4124–4134.

28 The (*E*/*Z*)-propenyl bromides, precursors of the vinyl stannane, is available overseas only as ship freight.

29 a) J. C. Cochran, S. C. Bayer, J. T. Bilbo, M. S. Brown, L. B. Colen, F. J. Gaspirini, D. W. Goldsmith, M. D. Jamin, K. A. Nealy, C. T. Resnick, G. J. Schwartz, W. M. Short, K. R. Skarda, J. P. Sprin and W. L. Strauss, *Organometallics*, 1982, **1**, 586–590; b) C. Li and J. A. Porco, Jr., *J. Org. Chem.*, 2005, **70**, 6053–6065; c) T. Choshi, T. Kumemura, J. Nobuhiro and S. Hibino, *Tetrahedron Lett.*, 2008, **49**, 3725–3728.

30 a) R. Shang, Q. Xu, Y.-Y. Jiang, Y. Wang and L. Liu, *Org. Lett.*, 2010, **12**, 1000–1003; b) R. Shang, Z.-W. Yang, Y. Wang, S.-L. Zhang, and L. Liu, *J. Am. Chem. Soc.*, 2010, **132**, 14391–14393.

31 M. Shi and K. M. Nicholas, *J. Am. Chem. Soc.*, 1997, **119**, 5057–5058.

32 a) P. Espinet and A. M. Echavarren, *Angew. Chem. Int. Ed.*, 2004, **43**, 4704–4734; b) C. Amatore, E. Blart, J. P. Genêt, A. Jutand, S. Lemaire-Audoire and M. Savignac, *J. Org. Chem.*, 1995, **60**, 6829–6839; c) G. Papadogianakis, J. A. Peters, L. Maat and R. A. Sheldon, *J. Chem. Soc. Chem. Commun.*, 1995, 1105–1106.

33 a) K. Curran, W. Risse, M. Hamill, P. Saunders, J. Muldoon, R. Asensio de la Rosa and I. Tritto, *Organometallics*, 2012, **31**, 882−889; b) L. K. Johnson and M. Brookhart, *J. Am. Chem. Soc.*, 1995, **117**, 6414−6415; c) L. H. Shultz, D. J. Tempel and M. Brookhart, *J. Am. Chem. Soc.*, 2001, **123**, 11539−11555; d) D. J. Tempel, L. K. Johnson, R. L. Huff, P. S. White and M. Brookhart, *J. Am. Chem. Soc.*, 2000, **122**, 6686−6700.

34 a) *The Organometallic Chemistry of the Transition Metals, 4th Ed.* R. H. Crabtree, Wiley, New York, USA, 2005, pp. 239–241; b) R. F. Heck, *J. Am. Chem. Soc.*, 1968, **90**, 5531–5534; c) J. M. Saá, G. Martorell and A. García-Raso, *J.* Org. *Chem.*, 1992, **57**, 678–685.

35 a) M. Kosugi and K. Fugami, *J. Organomet. Chem.*, 2002, **19**, 10–16; b) V. Farina, V. Krishnamurthy and W. J. Scott, *The Stille Reaction*, Wiley, New York, USA, 2004; c) S. H. Eitel, S. Jautze, W. Frey and R. Peters, *Chem. Sci.*, 2013, **4**, 2218–2233.

36 For examples of sequential homobimetallic catalytic transformations involving palladium, see: a) B. Gabriele, R. Mancuso, G. Salerno and M. Costa, *J. Org. Chem.,* 2007, **72**, 9278–9282; b) B. Gabriele, R. Mancuso, G. Salerno and L. Veltri, *Chem. Commun.*, 2005, 271–273; c) B. Gabriele, R. Mancuso, G. Salerno and M. Costa, *Adv. Synth. Catal.*, 2006, **348**, 1101–1109; d) B. Gabriele, R. Mancuso, E. Lupinacci, G. Salerno and L. Veltri, *Tetrahedron*, 2010, **66**, 6156–6161; e) B. Gabriele, R. Mancuso, G. Salerno and P. Plastina, *J. Org. Chem.*, 2008, **73**, 756–759.

37 For examples of sequential homobimetallic catalytic transformations involving ruthenium instead of palladium, see: a) B. Schmidt, *Eur. J. Org. Chem.*, 2003, 816–819; b) B. Schmidt and M. Pohler, *Org. Biomol. Chem.*, 2003, **1**, 2512–2517; c) J. Louie, C. W. Bielawski and R. H. Grubbs, *J. Am. Chem. Soc.,* 2001, **123**, 11312–11313; c) J. Gavenonis, R. V. Arroyo and M. L. Snapper, *Chem. Commun.*, 2010, **46**, 5692–5694.

38 a) E. Thiery, C. Chevrin, J. Le Bras, D. Harakat and J. Muzart, *J. Org. Chem.*, 2007, **72**, 1859–1862; b) A.-M. L. Hogan, T. Tricotet, A. Meek, S. S. Khokhar and D. F. O'Shea, *J. Org. Chem.*, 2008, **73**, 6041–6044; c) J. McNulty and K. Keskar, *Tetrahedron Lett.*, 2008, **49**, 7054–7057; d) J. Yu, M. J. Gaunt and J. B. Spencer, *J. Org. Chem.,* 2002, **67**, 4627–4629.

39 a) M. J. Spallek, S. Stockinger, R. Goddard and O. Trapp, *Adv. Synth. Catal.*, 2012, **354**, 1466–1480; b) M. Mayer, A. Welther and A. J. von Wangelin, *ChemCatChem*, 2011, **3**, 1567–1571; c) H.-Y. Li, X.-F. Li and H.-P. Zhang, *J. Chem. Res.*, 2013, **37**, 219–222; d) M. Thimmaiah, X. Zhang and S. Fang, *Tetrahedron Lett.*, 2008, **49**, 5605–5607; e) A. Falk, A.-L. Göderz and H.-G. Schmalz, *Angew. Chem. Int. Ed.*, 2013, **52**, 1576–1580; f) W. Rauf and J. M. Brown, *Angew. Chem. Int. Ed.*, 2008, **47**, 4228–4230.

40 a) D. Badone, R. Cecchi and U. Guzzi, *J. Org. Chem.*, 1992, **57**, 6321–6323; b) F. Berthiol, H. Doucet and M. Santelli, *Synthesis*, 2005, 3589–3602; c) L.-G. Xie and Z.-X. Wang, *Chem. Eur. J.*, 2011, **17**, 4972–4975; d) A. G. Maestri, S. D. Taylor, S. M. Schuck and S. N. Brown, *Organometallics*, 2004, **23**, 1932–1946.

41 I. A. Goodman and P. H. Wise, *J. Am. Chem. Soc.*, 1950, **72**, 3076–3079; b) M. R. Magerramov, S. T. Akhmedov, N. S. Sadykhov and C. A. Yusifov, *J. Org. Chem. USSR, Eng. Transl.*, 1973, **9**, 575–566.

42 a) S. E. Denmark and N. S. Werner, *J. Am. Chem. Soc.*, 2008, **130**, 16382–16393; b) H. B. Borate, S. H. Gaikwad, A. S. Kudale, S. P. Chavan, S. G. Pharande, V. D. Wagh and V. S. Sawant, *Tetrahedron Lett.*, 2013, **54**, 1528–1530; c) B. Greatrex, M. Jevric, M. C. Kimber, S. J. Krivickas, D. K. Taylor and E. R. T. Tiekink, *Synthesis*, 2003, 668–672; d) M. Matsumoto, S. Dobashi and K. Kondo, *Bull. Chem. Soc. Japan*, 1978, **51**, 185–187.